Flight Testing of an Advanced Airborne Natural Gas Leak Detection System

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Abstract

ITT Industries Space Systems Division (Space Systems) has developed an airborne natural gas leak detection system designed to detect, image, quantify, and precisely locate leaks from natural gas transmission pipelines. This system is called the Airborne Natural Gas Emission Lidar (ANGEL) system. The ANGEL system uses a highly sensitive differential absorption Lidar technology to remotely detect pipeline leaks. The ANGEL System is operated from a fixed wing aircraft and includes automatic scanning, pointing system, and pilot guidance systems. During a pipeline inspection, the ANGEL system aircraft flies at an elevation of 1000 feet above the ground at speeds of between 100 and 150 mph.

Under this contract with DOE/NETL, Space Systems was funded to integrate the ANGEL sensor into a test aircraft and conduct a series of flight tests over a variety of test targets including simulated natural gas pipeline leaks. Following early tests in upstate New York in the summer of 2004, the ANGEL system was deployed to Casper, Wyoming to participate in a set of DOE-sponsored field tests at the Rocky Mountain Oilfield Testing Center (RMOTC).

At RMOTC the Space Systems team completed integration of the system and flew an operational system for the first time. The ANGEL system flew 2 missions/day for the duration for the 5-day test. Over the course of the week the ANGEL System detected leaks ranging from 100 to 5,000 scfh.

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1.0 Executive Summary

The existing U.S. natural gas transmission infrastructure consists of over 300,000 miles of buried pipeline. DOE estimates that natural gas consumption will increase by over 50% percent (to 34 trillion cubic feet) by 2020, placing additional demands on the country's aging natural gas infrastructure. This combination of aging pipeline materials, increased demand, and utility deregulation presents an environment where natural gas emissions may occur with greater frequency and volumes. The reduction of these natural gas transmission pipeline emissions is critical to addressing several subjects of national importance, including: (1) natural gas conservation; (2) public and environmental safety; (3) greenhouse gas emissions; and (4) the overall cost of natural gas.

With the intent of improving the way pipelines are monitored for emissions, in 2001 a team of Space Systems scientists and external consultants was tasked to assess the ideal manner in which to remotely sense natural gas pipeline leaks from the air. Ultimately Differential Absorption Lidar (DIAL) technology was selected as the most sensitive and effective technique for detecting and quantifying the methane and ethane in gas pipeline leaks.

ITT Industries Space Systems Division (Space Systems) has developed an airborne DIAL system designed to detect, image, quantify, and precisely locate leaks from natural gas transmission pipelines. This system is called the Airborne Natural Gas Emission Lidar (ANGEL) system. The ANGEL System is operated from a fixed wing aircraft and includes automatic scanning, pointing, and pilot guidance systems. During a pipeline inspection, the ANGEL system aircraft operates at an elevation of 1,000 feet above the ground flying speeds of between 100 and 150 mph.

The objective of this effort was to flight test the ANGEL system in an operational environment. The two major phases of flight-testing for this effort consisted of early flight tests in Upstate New York, followed by participation in a DOE/DOT funded Field Test of Remote Sensing Gas Leak Detection Systems at the Rocky Mountain Oilfield Testing Center (RMOTC) near Casper Wyoming in September of 2004.

During early flight tests, the major objective was to debug sensor operation in the test aircraft and obtain initial characterization of ANGEL operation and capabilities. During this phase of the effort ITT successfully tested a range of sensor functionality including, ability to operate the system in test aircraft, laser power and stability, receiver system operation and sensitivity, pointing system performance and accuracy, and the ability to successfully process and analyze raw sensor data with ground processing algorithms and software.

In September, the Space Systems ANGEL System participated in a government funded field test of remote sensing leak detection systems. The United States Department of Energy, National Energy Technology Laboratory (NETL) and the United States Department of Transportation, Office of Pipeline Safety (OPS) jointly funded this field test. This field test was held from September 12-17, 2004 at the DOE's Rocky Mountain Oilfield Testing Center (RMOTC). RMOTC's field site is the Teapot Dome Field, 35 miles north of Casper, WY. The test was organized and run by the Southwest Research Institute (SWRI) in cooperation with the NETL, OPS, RMOTC, a number of pipeline industry advisors, and the remote sensing system technology providers. A total of 6 industry and government groups (technology providers) were invited to participate in this test.

During the DOE RMOTC field demonstration, the functionality of all major ANGEL systems was verified including gas detection, gas quantification, sensor targeting, laser scanning, data logging, data analysis, mission planning and flight operations. The system was flown at every opportunity from Sunday afternoon through Friday evening for a total of 11 flights. Approximately 80 gigabytes of raw data was collected for each day of operation. Although no usable DIAL data was collected on Sunday or Monday of the RMTOC demonstration, sensor performance data collected on these early flights allowed the ANGEL team to identify and repair a damaged optical component in the sensor. Much of the system's capability was untested prior to this demonstration and the event provided an unparalleled opportunity to operate, learn and ultimately improve the system.

Space Systems was pleased to participate in the DOE/DOT facilitated Demonstration of Remote Gas Leak Detection Systems at RMOTC. At this event we were able to demonstrate for the first time many aspects of the ANGEL System's capabilities. These included the ability to efficiently detect, quantify, geo-locate and image natural gas leak plumes from the air. During this demonstration the ANGEL team learned a number of very valuable lessons.

- We validated the concept of using Differential Absorption Lidar (DIAL) for gas leak detection and quantification from a fixed wing aircraft. Integration of the sensor into the test aircraft was completed at the Casper Airport. The first fully integrated ANGEL DIAL data <u>ever</u> collected was on 14 September 2004, the second day of the RMOTC test. The ANGEL system was successful at detecting and quantifying a majority of leaks of 500 scfh and larger.
- We confirmed that the ANGEL Intelligent Pointing and Scanning System allowed the aircraft to fly the Virtual Pipeline end-to-end at high speed and inspect 100% of the pipeline on a single pass. The ability to collect data accurately, rapidly, and efficiently is critical to future commercial operations.
- We challenged the Beta version of our ground data processing software and it worked well throughout the week. The experience of having to rapidly process vast quantities of data during the demonstration is currently driving major improvements in the area of automated data processing and analysis.
- We verified the relationship between laser output power and our ability to detect leaks. This was one of the most important lessons learned at RMOTC. Increasing laser power greatly improves our ability to lock on a set wavelength and greatly improves the signal to noise ratio of the data.

Our understanding of the phenomenology of DIAL gas leak detection has been greatly improved by our participation in this effort. Over the course of this study we imaged gas leak plumes of various sizes and shapes literally hundreds of times. The data collected during this study has been invaluable for gaining a better understanding gas leak behavior under a range of real-world conditions.

2.0 Report Details

2.1 Experimental Methods

2.1.1 Background

The existing U.S. natural gas transmission infrastructure consists of over 300,000 miles of buried pipeline. DOE estimates that natural gas consumption will increase by over 50% percent (to 34 trillion cubic feet) by 2020, placing additional demands on the country's aging natural gas infrastructure. This combination of aging pipeline materials, increased demand, and utility deregulation presents an environment where natural gas emissions may occur with greater frequency and volumes. The reduction of these natural gas transmission pipeline emissions is critical to addressing several subjects of national importance, including: (1) natural gas conservation; (2) public and environmental safety; (3) greenhouse gas emissions; and (4) the overall cost of natural gas.

In the U.S., by regulation, all Class 1 and Class 2 pipelines must be inspected for leaks at least once each calendar year. Class 3 and 4 pipelines must be inspected 2 to 4 times each year. Current pipeline leak detection methods rely heavily on inspection crews walking (1–2 mph) or driving slowly (4 mph) along the right of way using flame ionization detectors to sample the air and detect the presence of hydrocarbons at, or near ground, level. This technique is slow, inefficient, and prone to false alarms. Recently developed, truck-mounted optical systems that detect methane are an improvement in some situations but are still quite limited.

With the intent of improving the way pipelines are monitored for leaks, a team of Space Systems scientists and external consultants was tasked to assess the ideal manner in which to remotely sense natural gas pipeline leaks from the air. Participants in this study included world-class experts in active and passive remote sensing and experts in the integration of remote sensing instruments into light aircraft. The approaches investigated included: *Hyperspectral Imaging* (HSI), *Radar Imaging*, *Backscatter Absorption Gas Imaging* (BAGI), *Gas Correlation Spectroscopy* (GCS), *Active Gas Correlation Spectroscopy* (AGCS), and *Differential Absorption Lidar* (DIAL) [3]. This investigation indicated that an active remote sensing approach, using DIAL, would be the most sensitive and effective technique for detecting and quantifying the methane and ethane in natural gas pipeline leaks.

2.1.2 Objective

The objective of this effort was to flight test a high sensitivity, broad-coverage, natural gas leak detection systems in an operational environment. Space Systems Airborne Natural Gas Emission Lidar (ANGEL) System was designed to accurately detect, image, quantify, and geo-locate leaks from natural gas transmission pipelines. The system operates in a wide variety of terrain and weather conditions. The ANGEL System, when used commercially, will provide a major breakthrough in speed, cost effectiveness, and safety of monitoring the nation's natural gas transmission pipeline system [1]. The two major phases of flight-testing for this effort consisted of early flight tests in Upstate New York, followed by participation in a DOE/DOT funded Field Test of Remote Sensing Gas Leak Detection Systems at the Rocky Mountain Oilfield Testing Center (RMOTC) near Casper Wyoming in September of 2004.

2.1.3 The Physics behind DIAL gas detection

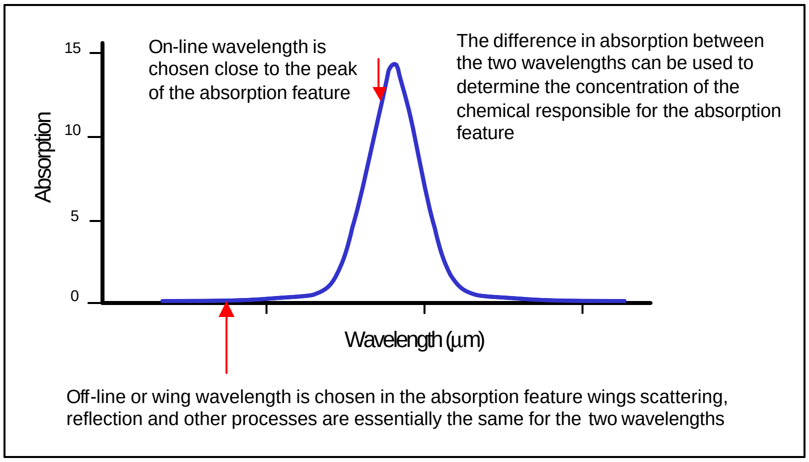

Figure 1. Generic representation of DIAL on-line and off-line positions

Our chosen method of detecting methane plumes is an active remote sensing technology known as Differential Absorption LIDAR (DIAL). DIAL is the use of at least two beams of light tuned on and off of an absorption feature of the gas species to be measured. By comparing the light from the on-resonance beam to the light in the off-resonance beam, the concentration of gases from long range may be inferred (Figure 1).

Our design uses lasers to generate the light beams. The system takes light reflected from the ground to generate a signal on a detector. Each wavelength is detected separately. The basic LIDAR equation describing the light reflected from the surface is shown in Figure 2.

$$\underbrace{E(l)}_{\text{Received Pulse Energy}} = \underbrace{P_L t_d}_{\text{Transmitted Pulse Energy}} \times \underbrace{x(l)x(R_T)}_{\text{Beam Alignment and Optical Spectral Properties}} \times \underbrace{\frac{D^2}{4R^2}}_{\text{Receiver Solid Angle Effects}} \times \underbrace{r(l)}_{\text{Surface Reflectance Effects}} \times \underbrace{T_{atm}^2}_{\text{Atmospheric Extinction Effects}} \times \underbrace{\exp\left(-2\int_0^R N(R)s(l)\,dR\right)}_{\text{Methane Dependence}}$$

Figure 2. Basic DIAL equation

The term E(λ) is the energy contained in the pulse that has traveled to the ground and back. This return energy depends on many things as expressed by the right hand side of the equation. The first term on the right hand side, gives the per-pulse energy of the transmitter. The second term combines effects from the optical system alignment and spectral response. The next term shows the effect of the receiver solid angle. These terms are governed largely by the lidar optical design. The next two terms show the dependence on the surface reflectivity (assumed Lambertian in this equation) and the atmosphere. The final term shows the effect of the concentration of methane, N(R), and the optical properties of methane as represented by $s(l)$, the methane absorption cross-section.

These return signals are used to determine the methane concentration multiplied by the depth of the methane plume. This quantity is called the concentration path length or CPL and is given by the following equation:

$$CPL = Nh = \frac{C}{2s(l)}\left(\ln\left(\frac{E_{off}}{E_{on}}\right)\right)$$

The CPL is an integrated concentration and can be thought of as giving a measure of the concentration of a cylindrical shaped sample of the plume of height (or path length) h. (Figure 3)

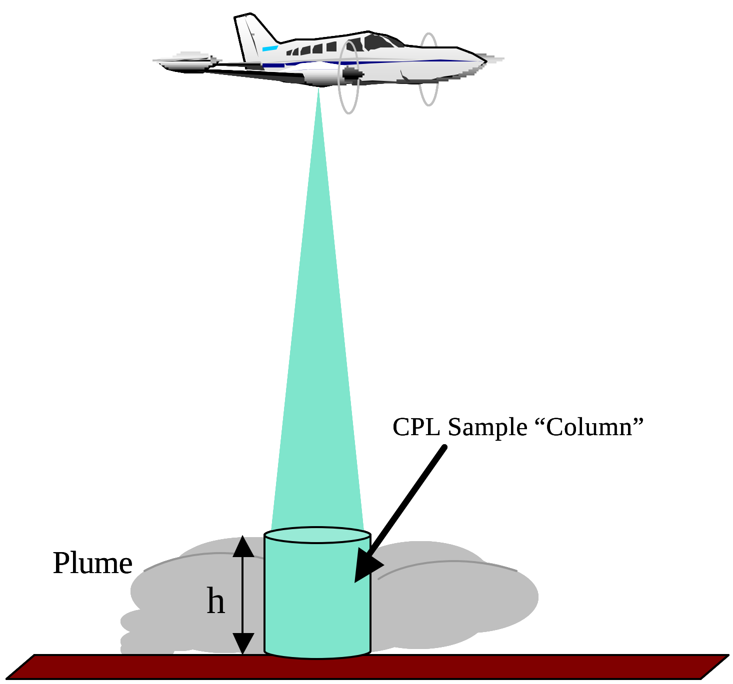

Figure 3. Concentration Path Length (CPL) of a plume as measured from an aircraft.

The signal to noise ratio (SNR) for any given measurement determines the sensitivity of the system and will be the number of signal photons divided by the total noise of the system and solar reflected and thermal background photons incident on the system during the measurement and other effects such as scintillation in the atmosphere and speckle, a surface roughness effect. Both will reduce the overall SNR in a real system.

2.1.4 ANGEL System Overview

The DIAL Sensor in the ANGEL System [4] is built around solid-state laser sources (Transmitter) combined with a telescope system (receiver) to collect the laser light reflected from the ground surface. Figure 4 provides an artist conceptual drawing of the in-flight survey of a natural gas transmission line right-of-way.

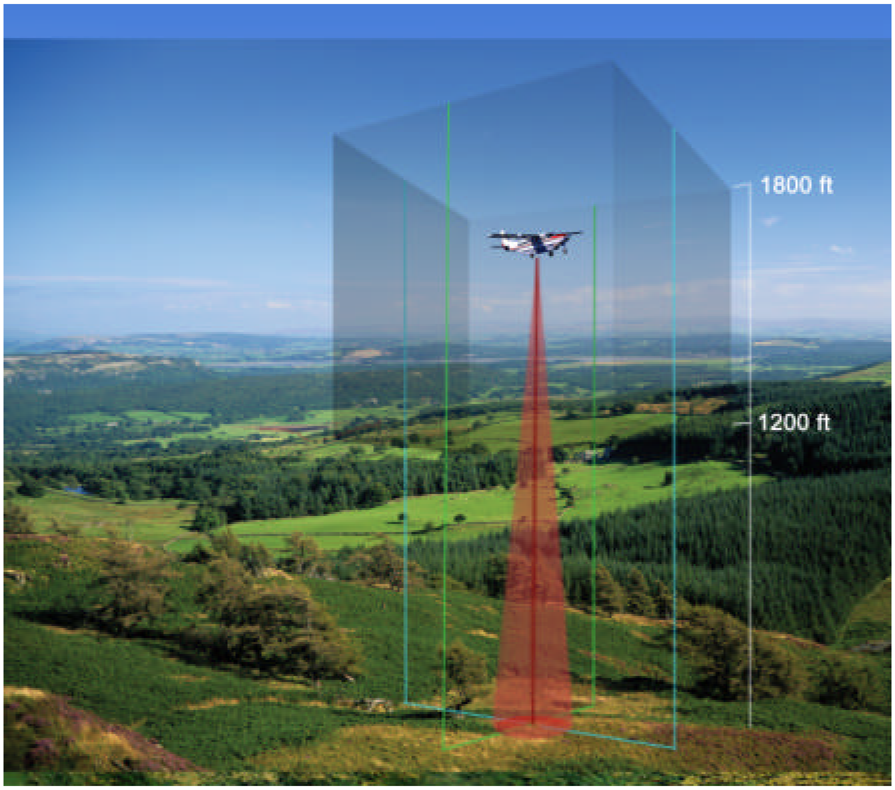

Figure 4 Conceptual view of the airborne ANGEL Service capturing leak survey data along a pipeline right-of-way.

In addition to the DIAL transmitter and receiver subsystems, the ANGEL System onboard the aircraft includes a computer controlled pointing and scanning subsystem designed to compensate for aircraft motion while keeping the lasers scanning over pipeline. For a typical flight operation, the Operations Center provides mission planning data for a selected pipeline to the flight crew. This data is loaded into the airborne system. The aircraft and crew then proceed to the starting point for a pipeline survey and fly the pre-selected natural gas pipeline route. During the flight, the Payload ingests and records precise real-time position and attitude data. This positional information is then used in conjunction with the targeting data from the Operations Center to assure the continuous collection of raw sensor data along the route.

A scanning subsystem allows the collection of data over a wide swath of ground as the aircraft flies above the right-of-way. The System also provides navigational aids to the pilot to assure the aircraft is located in the correct position, thus allowing the pointing and scanning subsystems to accurately acquire data over the pipeline right-of-way. Use of an automatic scanning and pointing system combined with a pilot navigational aid allows the ANGEL system to fly a smooth route while collecting data over a very irregular pipeline (Figure 5).

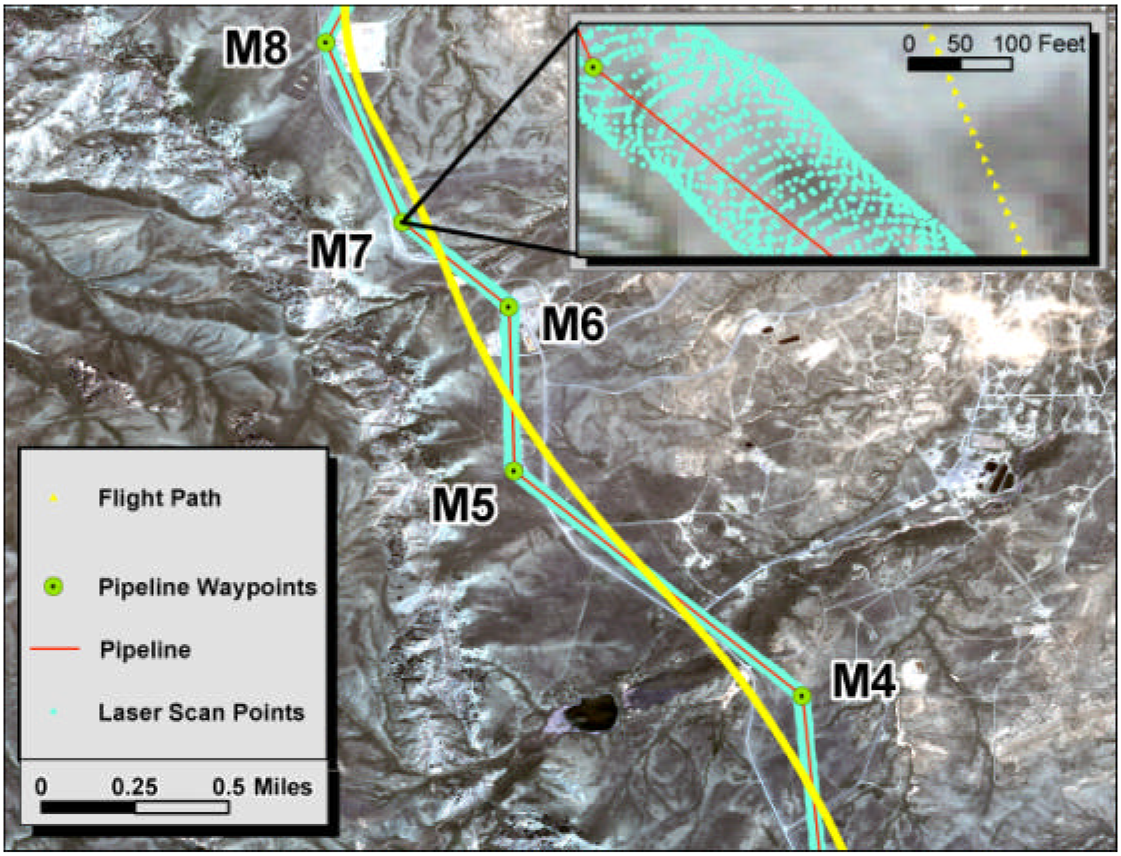

Figure 5 Space Systems ANGEL pointing results from a short section of the Virtual Pipeline Route at RMOTC. The aircraft path is shown in yellow. The pipeline position is shown in red. The position of each data point is shown in green forming a coverage swath 110 feet wide. The sensor pointing and scanning system allows full coverage of the ROW corridor in a single pass.

2.1.4.1 Aircraft Platform Description

The airborne portion of the ANGEL System consisted of a test aircraft and an integrated sensor payload. The test aircraft used was a modified Air Force owned Convair 580 (NC-131H) Turboprop known as the Total In-Flight Simulator (TIFS), operated by General Dynamics. This aircraft was used for both Early Flight Testing and for the Field Test at RMOTC. The TIFS aircraft shown in Figure 6 is illustrated in Figure 7. Although the ANGEL System was later integrated into a much smaller (and more economical) Cessna Grand Caravan following early flight tests, the TIFS aircraft was chosen for early flight tests in order to accelerate the development schedule and allow the ITT team to participate in the DOE sponsored RMOTC field test in Wyoming. The TIFS aircraft is a very large and very powerful test aircraft with ample room for the sensor and multiple operators, easy access to the sensor once installed, ample electrical power, payload carrying capacity, and a history of carrying FAA approved experimental payloads. The skilled General Dynamics test pilots, flight crew, and ground crews mitigated the risk of conducting early flight tests on an accelerated schedule. Early integration and testing in the TIFS aircraft greatly simplified the later integration of the sensor into the much smaller Cessna aircraft.

Figure 6. Space Systems' ANGEL System test aircraft – General Dynamics Convair 580 (NC-131H) turboprop landing at the Natrona County International Airport, Casper, Wyoming

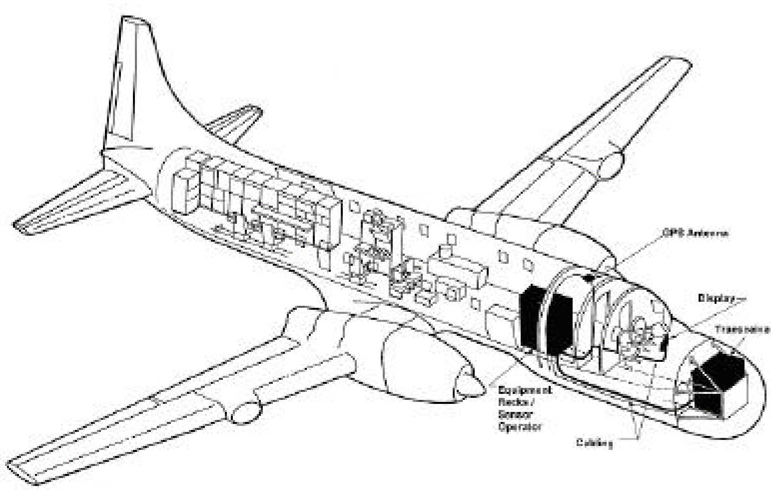

Figure 7. Diagram of Space Systems ANGEL System Test Aircraft illustrating placement of the major sensor components.

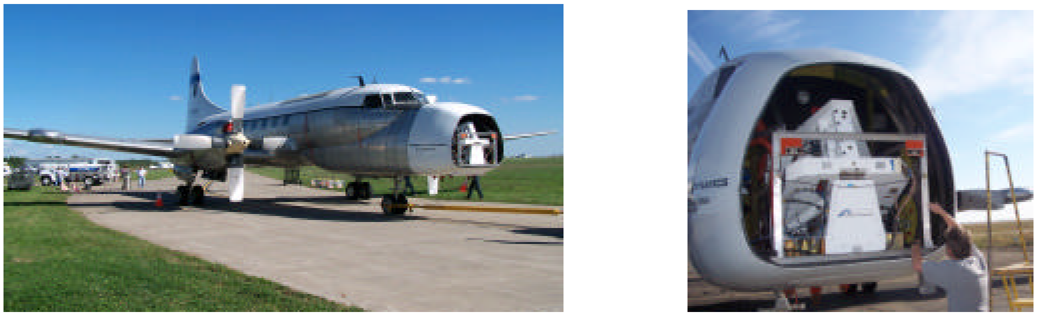

Figure 8. Space Systems ANGEL System Test Aircraft showing placement of the transceiver in the nose of the aircraft during preparation for early flight tests in Buffalo, NY.

The Payload used in the early flight-testing phase of sensor development is the same basic hardware and software that will be used in commercial operations. In general, the Payload consists of a Transceiver Assembly, two aircraft electronic Rack Assemblies, cables, and other miscellaneous hardware and software. Payload integration within the TIFS flight test aircraft is illustrated in Figure 8.

The DIAL data, continuous aircraft positional data (yaw, pitch, roll), sensor performance data, and meta-data such as atmospheric pressure and temperature are recorded on the aircraft on a removable hard drive. On-board digital camera data used to record imagery of the survey route (Figure 9) in real time is recorded to writeable DVD as a separate data set.

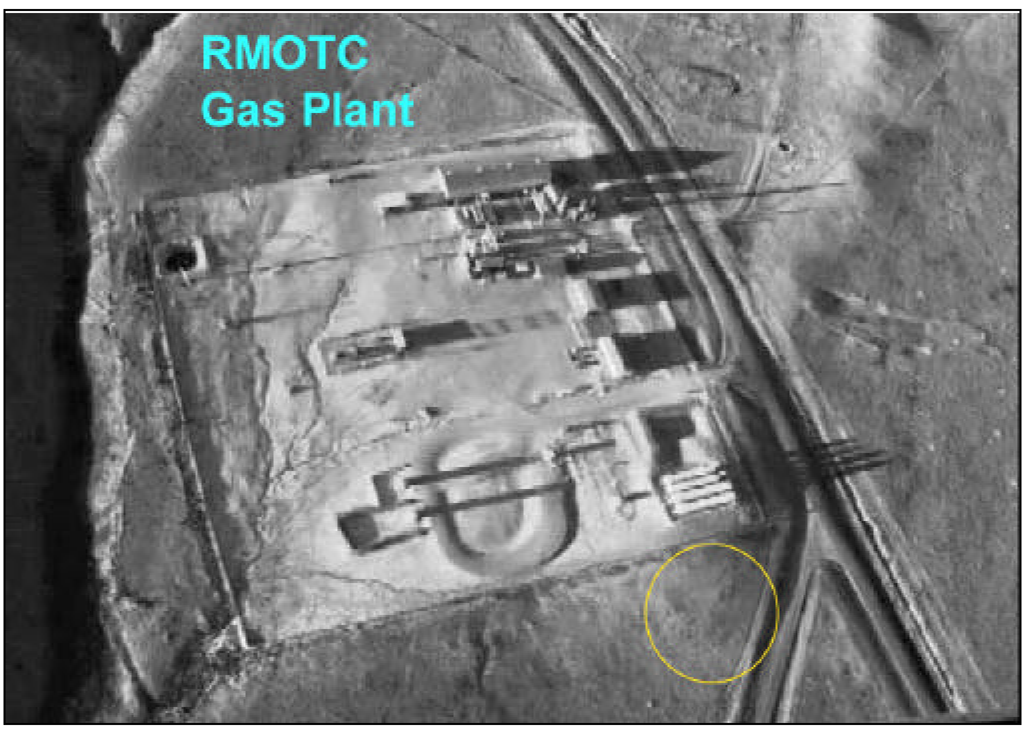

Figure 9 Aerial view of the Gas Plant at the Rocky Mountain Oilfield Testing Center acquired with the ANGEL Sensor engineering camera. The yellow circle indicates the approximate position of a leak detected with the DIAL subsystem.

2.1.4.2 Data Processing and Analysis

A major element of the ANGEL System is the Operations Center where data is processed and analyzed. Once the aircraft lands, data is transferred from the aircraft to the Operations Center and archived to ground storage disks. The sensor data is processed using software based on Space Systems' proprietary DIAL/Lidar algorithm set. During initial processing, data points are geo-located and assessed for the presence of the natural gas. The level of gas detected is computed in terms of concentration path length (CPL).

The output of the processing step includes 1) GIS shape files that will be used by analysts to create customer reports and 2) engineering data that details sensor and related subsystem performance. Space Systems engineers use this latter information to assess data quality and to compensate for various environmental, surface and operational variables that can effect data interpretation.

GIS maps of CPL measurements are used to create a visual graphic of elevated gas concentrations (Figure 10). This data is then interpreted visually and run through additional algorithms to automatically identify the presence and quantity of natural gas. Reports and visualizations are generated using Space Systems ANGEL Pipeline Visual Inspection and Analysis Software – APVIAS. The APVIAS software package is based upon Space Systems' wholly owned subsidiary Research Systems Inc. IDL/ENVI software and has been customized for the analysis and interpretation of ANGEL data. The ANGEL data is fully geo-referenced so analysts can overlay the ANGEL data with other geo-referenced images or DEMs to aid in interpretation.

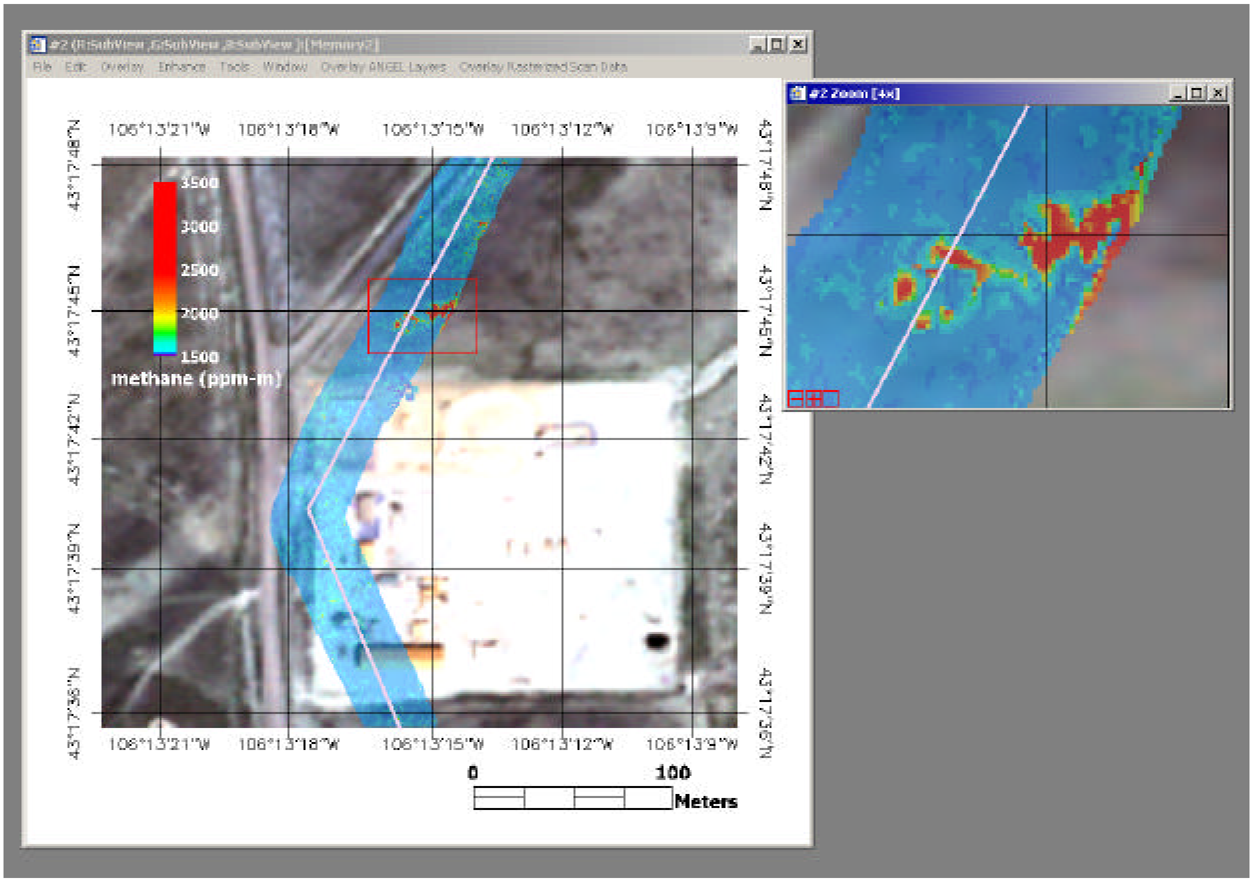

Figure 10 Detection, quantification, visualization, and geolocation of a natural gas plume at RMOTC.

2.2 Results and Discussion - Early Flight Tests (Buffalo, NY)

2.2.1 Objective of Early Flight Tests

The objective of the first three flights was to concentrate on verifying the following basic ANGEL sensor functionality:

- Demonstrate the sensor can operate in the Convair 580 environment and determine typical physical flight characteristics relating to sensor operation including vibration, temperature and that it can operate with aircraft power.
- Demonstrate that the lasers maintain power output throughout the flight.
- Demonstrate robustness of laser frequency locking mechanism.
- Demonstrate the receiver system can receive adequate laser energy regardless of ground reflectivity.
- Demonstrate the pointing system meets accuracy requirements.
- Demonstrate the post mission data processing system can process the raw ANGEL sensor data and produce acceptable results.

The initial flight tests were intended to debug sensor operation in the test aircraft and obtain initial characterization of ANGEL operation and capabilities. This section describes the test flight sequence prior to departure for the Department of Energy demonstration exercise in Casper, Wyoming.

2.2.2 Creation of a simulated natural gas leaks for flight testing

Over the summer of 2004 the Space Systems team worked with National Fuel gas Pipeline Company in upstate New York with the goal of creating a series of simulated leaks along actual pipeline Rights-of-Way in Upstate New York. Early planning efforts included a physical survey of the Empire Pipeline and an assortment of other National Fuel lines and facilities between Rochester and Buffalo. Two sites along the pipeline were selected as ideal for the creation of moderate to large natural gas leaks (Figure 11). The sites chosen were on property owned by National Fuel, close to the airport and away from public roads. Ultimately only the sites closest to the airport were used to create simulated leaks.

Figure 11. Map showing the location of the Niagara Frontier Airport and 2 sites selected for possible simulated leaks along the Empire Pipeline (shown in purple).

During early flight testing, National Fuel supplied gas for the simulated leaks using a set of portable high pressure natural gas storage tanks mounted on a trailer. Gas from these tanks was run through a 2-stage regulator to control the release rate and flowed through a 30 foot length of copper tubing to the actual release site. A flow meter was used to accurately set the regulator to a given release rate before each ITT Industries ANGEL System overflight. At the actual simulated leak site the copper tube was run to the bottom of an 18 inch deep post hole filled with coarse gravel. A heavy weight was place on the copper tube at the leak site to prevent movement of the copper tube during large releases. Calibrated natural gas leaks from near 0 to 5,000 standard cubic feet per hour (scfh) were possible with this setup(Figure 12).

Figure 12. Image of a simulated natural gas leak site along a pipeline right-of-way near Buffalo, New York.

The DOE used a very similar simulated leak setup for many of the smaller leaks at the Rocky Mountain Area Test Center [2].

During each release, the simulated leak site was instrumented with a portable meteorology station equipped with a data logger to record wind speed, direction, and a range of other weather measurements at one minute intervals. The ground test team was equipped with air-to-ground radios to allow communication with the aircraft crew. Gas releases were started one to two minutes before the aircraft was overhead and shut off after the aircraft passed over the target.

One major advantage of selecting the Empire Pipeline system for flight testing was the availability of recently acquired GIS information for these lines. GIS information supplied by National Fuel combined with GPS locations of selected simulated leak sites were used to create Mission Planning files to guide the pilot and point the sensor. GIS information from National Fuel was draped over publicly available 1-meter geo-referenced imagery of the area (Figure 13) to roughly verify the accuracy of the GIS data and ultimately to provide context to the data collected.

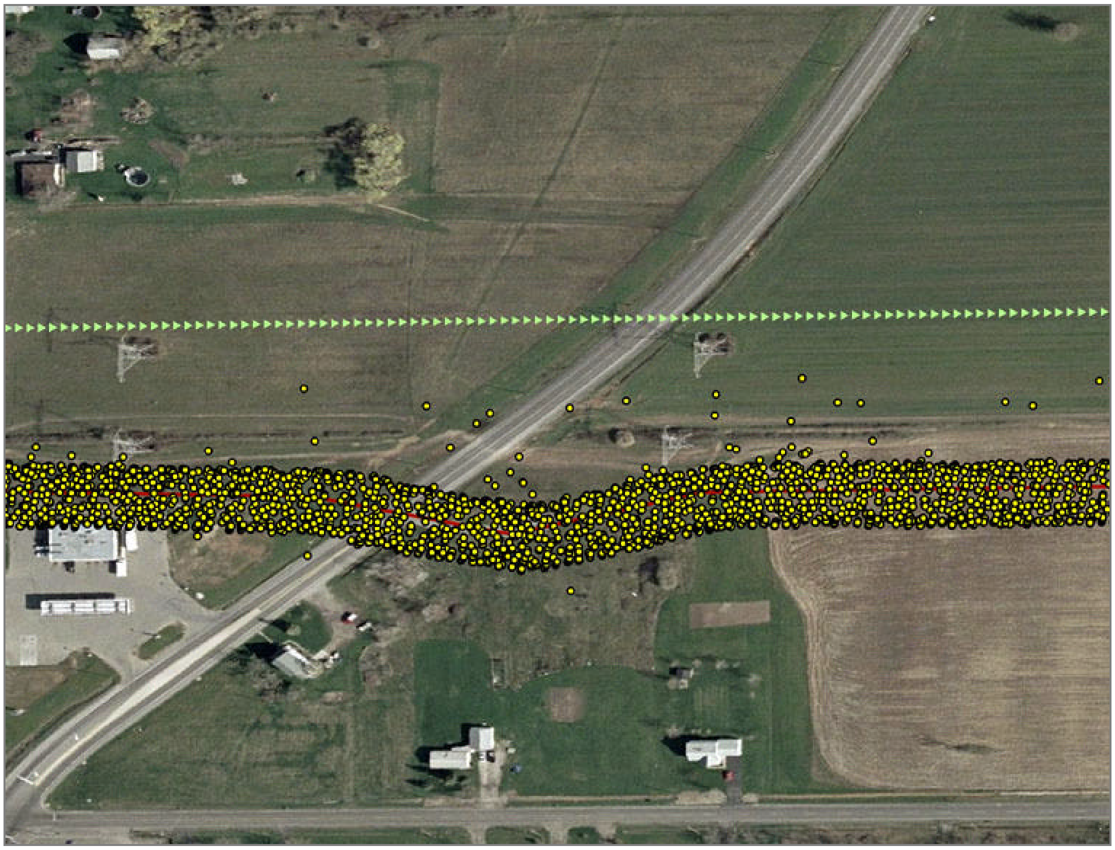

Figure 13. A geo-referenced color image of the pipeline right-of-way is used as a base GIS raster imagery layer. The GIS vector layer of the pipeline supplied by National Fuel is indicated in red, the track of the ANGEL system aircraft as it flew the line is marked in green. Yellow dots indicate the position of individual laser spots along the inspection swath of the DIAL system.

2.2.3 Flight One – (3 September 2004)

2.2.3.1 Objectives

The objectives of the first flight were to fly multiple events over pre-determined ground based test targets. The first flight was scheduled over a calibrated gas leak to collect data for basic sensor functionality characterization. The second event was to fly a series of passes over an accurately geo-located building to calibrate the system's geo-location capabilities. The third event was to again pass over a calibrated leak to see if natural gas could be detected.

2.2.3.2 Results

During this first flight the ANGEL System encountered multiple difficulties. The sensor computer went down during this flight and despite multiple attempts to recover operations no useful DIAL data was collected. Total time in the air was 1 hour and 23 minutes. Software fixes were implemented at the conclusion of the flight to remedy the problems encountered.

2.2.4 Flight Two – (3 September 2004)

2.2.4.1 Objectives

The original objectives for the second flight were to continue attempts to detect natural gas. Due to the difficulties experienced during the first flight, the flight plan attempted on flight number Two were scaled back and focused solely on detection of simulated leaks

2.2.4.2 Results

The aircraft shutter door could not be operated properly because of an aerodynamic pressure differential problem. Future flights were initiated with the shutter door slightly opened to equalize pressure and allow the shutter to easily be retracted the rest of the way in flight.
Total time – engine running - ~1 hours and 26.5 min.

2.2.5 Flight Three – (7 September 2004)

2.2.5.1 Objectives

The main goal of the third flight was to again to get a general idea of the performance of the sensor. Secondary objectives were to observe the pointing accuracy of the sensor. Prior to the third flight, software changes were made to various program elements to improve reliability.

2.2.5.2 Results

This flight was the first time that DIAL data was successfully collected from the air. The weather on this flight, however, became a problem. Rain coupled with low ceilings made the flight challenging.

The robustness of inter-computer communications software needed be addressed prior to deployment to RMOTC. Software guiding the pilot required modification as the flight path flown was several hundred yards to the east of the pipeline right of way. Although no DIAL data was collected over the simulated leak site, DIAL data was collected over nearby agricultural areas and trees providing confidence that our pointing accuracy could be greatly improved with a software adjustment during ground data processing. GIS processing of the data to plot range to target info for each offline laser pulse resulted in a crude 3-Dimensional lidar image of the ground and vegetation under the plane (Figure 14). When flying at 1,000 feet, the conical scan pattern generated by the sensor provided excellent coverage of a > 100 foot wide swath. Early DIAL measurements of methane concentration over agricultural areas and forests proved to be very noisy, particularly over forested areas (Figure 15). Improving system signal to noise characteristics remained a major focus of the engineering and analytical teams.

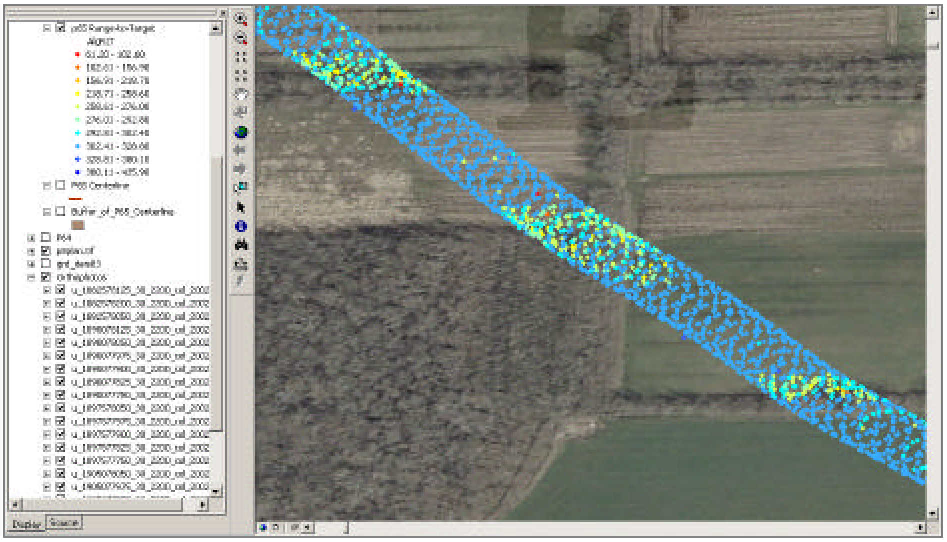

Figure 14. First airborne DIAL data set from the ANGEL sensor processed color-coded for range-to-target (distance from the sensor to the land surface). Areas colored blue correspond to agricultural fields (low vegetation = greater range to target), Yellow areas of the scan swath roughly correspond to forested areas which reflect the laser light before it gets to the ground and results in a smaller range-to-target values. low areas

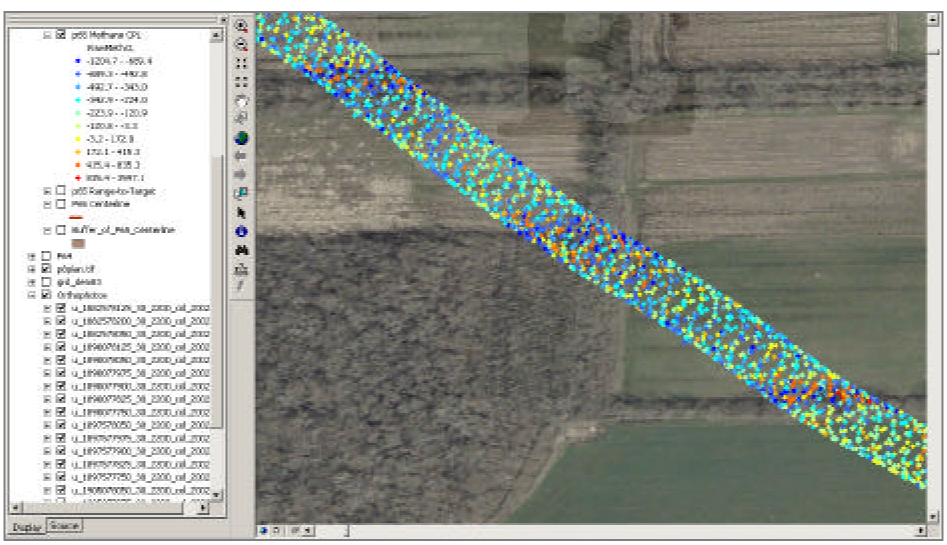

Figure 15. First airborne DIAL data set from the ANGEL sensor processed color-coded for methane concentration path length (CPL). Methane CPL in this "first light" image are highly variable and greatly effected by vegetation. A variety of hardware and software have been implemented to improve the quality the ANGEL data.

2.2.6 Conclusions from early flight tests

The operation of the system improved on every flight. Several additional flights were highly desired to get the sensor ready for the DOE Field Test of remote sensing leak detection systems in Wyoming. With no time left to debug the sensor, the decision was made to deploy to Wyoming and attempt to finish the sensor integration in conjunction with the DOE Field Test.

2.3 Overview of RMOTC Field Test (Casper, WY)

In 2004, the Space Systems ANGEL System participated in a government funded field test of remote sensing leak detection systems. The field test was held at the DOE's Rocky Mountain Oilfield Testing Center (RMOTC). RMOTC's field site is the Teapot Dome Field, 35 miles north of Casper, WY (Figure 16). The United States Department of Energy, National Energy Technology Laboratory (NETL) and the United States Department of Transportation, Office of Pipeline Safety (OPS) jointly funded this field test. The test was organized and run by the Southwest Research Institute (SWRI) in cooperation with the NETL, OPS, RMOTC, a number of pipeline industry advisors, and the remote sensing system technology providers. A total of 6 industry and government groups (technology providers) were invited to participate in this test [2]. RMOTC's field site is the Teapot Dome Field, 35 miles north of Casper, WY (Figure 17). The field test was held from September 12-17, 2004 after a number of months of planning and preparation. ITT involvement in early planning for the field test consisted of numerous telcons throughout the year, participating in Advisory Panel meetings and Field trips (Figure 16 & Figure 17) to the proposed test area with test organizers and other participants in March and June.

Figure 16. Photograph of the RMOTC test area taken from RMOTC headquarters building.

Figure 17. Inspection of Proposed Virtual Pipeline Route at RMOTC in June 2004.

RMOTC was established by the U.S. Department of Energy (DOE) to partner with the petroleum industry to improve domestic oil and gas production through the field testing of new technology, evaluation of new equipment, and demonstration of new processes. The field test site is a 10,000-acre operating oil field. There are approximately 1,200 well bores and approximately 600 producing oil and gas wells, in nine producing reservoirs ranging in depth from 500 ft. to 5000 ft.

For this test, a virtual pipeline route approximately 7.55 miles in length was set up by the test organizers at the western edge of the RMOTC area (Figure 18). The test organizers created a series of leak sites along this virtual pipeline to simulate pipeline leaks of a variety of sizes. Leaks ranged in size from 1 standard cubic feet per hour (scfh) to 5,000 scfh. With the exception of a known calibration leak on the southern end of the test course, the size and location of each of the leak sites were hidden by the test organizers and remained unknown until after each of the test participants submitted their final leak detection report.

Participants in the RMOTC Field Test fielded a range of different sensors operated from ground vehicles, fixed wing aircraft, helicopter, and UAV platforms. One of the major challenges of using a sensor at RMOTC was the relatively windy condition. During planning meetings with the test organizers in early 2004, the Space Systems team requested flight times in the early morning and late afternoon to avoid the mid-day atmospheric turbulence and high winds. Test organizers provided a 50-minute inspection time slot on each day of the test September 13-17 (a total of 10 inspection times). In addition, Space Systems was provided a 50- minute practice time slot on Sunday September 12th before the start of the test. Leak rates and locations were changed daily throughout the test.

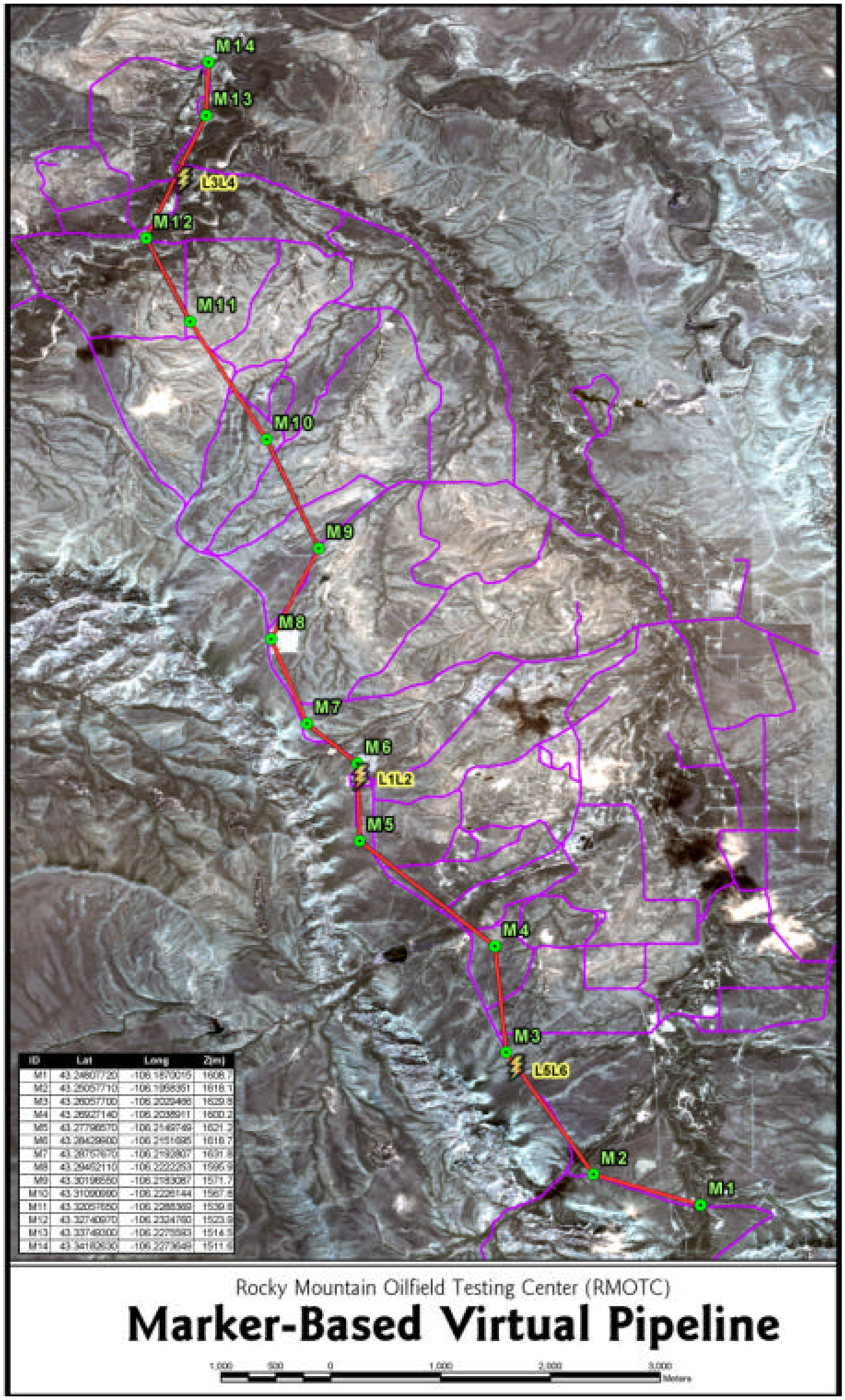

Figure 18. Map of the Marker-Based Virtual Pipeline along the western edge of the Rocky Mountain Oilfield Testing Center in Wyoming. Virtual pipeline in shown in Red, 14 pipeline markers of known location are shown in green, meteorology stations are shown in yellow.

2.3.1 RMOTC Field Test

Between the days of Sunday, 9/12/2004 to Friday, 9/17/2004, ITT Industries deployed a total of 26 employees and subcontractors to Casper Wyoming to participate in the RMOTC Field Test. The ITT team consisted of the aircraft pilot and crew, sensor operators, and a team of engineers, scientists, and leadership at hanger and ground data processing facilities at the Casper Airport (Figure 19 and Figure 20).

Figure 19. ITT Industries ANGEL system test aircraft in Casper, Wyoming

Over the course of the week the test aircraft flew and collected data during every available time slot. A total of 11 flights were conducted from Sunday, 9/12/2004 to Friday, 9/17/2004. A detailed description of each of these flights is included in Attachment 1.

After some initial problems on Sunday and Monday, large amounts of usable DIAL data was collected from Tuesday through Friday. The RMOTC Virtual Pipeline was 7.5 miles in length and the test aircraft was able to inspect the entire Virtual Pipeline route 6 to 7 times in each 50-minute window. Although the RMOTC Virtual Pipeline contains a number of relatively sharp turns, the ANGEL Sensor's intelligent pointing and scanning subsystem combined with the pilot guidance system allowed coverage of 100% of the pipeline route in a single pass.

At RMOTC the ANGEL sensor collected approximately 3 gigabytes of data for each complete pass. During every pass the sensor measured for the presence of methane more than 250,000 times. This allowed the creation of a methane map the entire length of the pipeline. By the end of the week the Space Systems Ground Data Processing team filled a 500 gigabyte server hard drive with raw and processed ANGEL data.

Figure 20. ITT Industries RMOTC Field Test Operations Center at the Casper Airport

Figure 21. Pilots view of the RMOTC test area from 1,000 feet

2.4 RMOTC Summary and Discussion

During the DOE RMOTC field trials, the ITT ANGEL System verified the function of all major systems including gas detection, gas quantification, sensor targeting, laser scanning, data logging, data analysis, mission planning and flight operations. The system was flown at every opportunity from Sunday afternoon through Friday evening for a total of 11 flights and 58 field passes. The sensor collected approximately 80 gigabytes of data each day. Sensor pointing and laser scanning systems successfully provided 100% pipeline corridor coverage. Given that much of the system's total performance was untested prior to these trials, the event provided an extraordinary opportunity to test, learn and improve the system.

During each pass the sensor measured the concentration path length of methane more than 250,000 times, allowing the creation of a methane map for the entire length of the pipeline. Emissions were detected at a number of locations along the virtual pipeline on Tuesday, Wednesday, Thursday and Friday. Results were reported as high confidence when signals indicating high concentration path length (CPL) were detected on multiple passes of both morning and afternoon flights. The degree of confidence was proportional to the number of detections.

The ANGEL System was constrained during this field test by three known system level limitations. These constraints led to reduced performance throughout the week and were not addressable until the system was returned to the lab following the field trials. The three primary limitations of the system were:

1. Reduced laser output power. Overall, during the RMOTC field trial, the ANGEL system was producing less than 50% of the normal operating laser output power. Laser power is directly linked to low-end gas detection ability. Many of the issues related to reduced laser output power were traced and attributed to the coated optics. Although some basic sensor repairs and adjustments were completed in the hanger at Casper, more involved sensor repairs/upgrades could only be completed at ITT facilities after the conclusion of the RMOTC effort.
2. Disabled ethane detection laser bench. The system is designed for detection of both methane and ethane via companion laser benches tuned to different absorption frequencies. Prior to leaving for RMOTC, the ethane laser bench was not functioning properly and was taken "off-line" for the event. The detection of ethane with methane is a telltale sign of natural gas and significantly reduces the potential of false alarm due to various and abundant natural sources of methane.
3. Signal degradation with the scanner optics. The computer controlled scanner moves the lasers across the right-of-way as the plane flies its route. Throughout the week the scanner was able to consistently and accurately scan the lasers above the pipeline, yet performance issues within the scanner significantly contributed to overall system "noise" and degraded signal detectability.

RESULTS

The final report on "Field Testing of Remote Sensor Leak Detection Systems" included a complete set of sensor performance data for all test participants and was published by the DOE in 2005. Following submission of the ITT final reports to the RMTOC Field Test Organizers (included as Attachments 1-5), ITT was provided the actual location and size of the leaks.

Table 1 - Leaks detected during the RMOTC Field Test

Leak_ID	Gas Source	Leak Type	Size_Tues	Detected?	Size_Wed	Detected?	Size_Thu	Detected?	Size_Fri	Detected?
1	RMOTC gas	below ground	1000	1	500	0	100	1	15	
	RMOTC gas	below ground							5000	1
2A	cylinder	below ground							15	0
2B	cylinder	below ground								
2C	cylinder	below ground			15	0				
3	RMOTC gas	above ground	2000	1	100	0	2000	1	500	0
4	RMOTC gas	below ground	500	0	2000	1	1000	0	2000	0
2D	cylinder	below ground	15	0						
5	RMOTC gas	below ground	5000	1	5000	1			5000	1
P1	RMOTC gas	side-drilled	1000	0	1000	0	1000	1	1000	0
P2	RMOTC gas	side-drilled	100	0	100	0	100	0	100	0
6	RMOTC gas	below ground	100	1	1000	0	500	0	1000	1
2E	cylinder	below ground					15	0		
P3	RMOTC gas	side-drilled	10	0	10	0	10	0	10	0
P4	RMOTC gas	side-drilled	500	1	500	1	500	0	500	0
P5	cylinder	side-drilled	1	0	1	0	1	0	1	0

The data in Table 1 is a summary of leaks created by the test organizers combined with a list of what leaks were detected and successfully reported during each day of the week. Figure 22 provides an overview of the leaks detected at RMOTC from September 14-17. This figure clearly indicates that the larger the leak the more likely the ANGEL system would detect it.

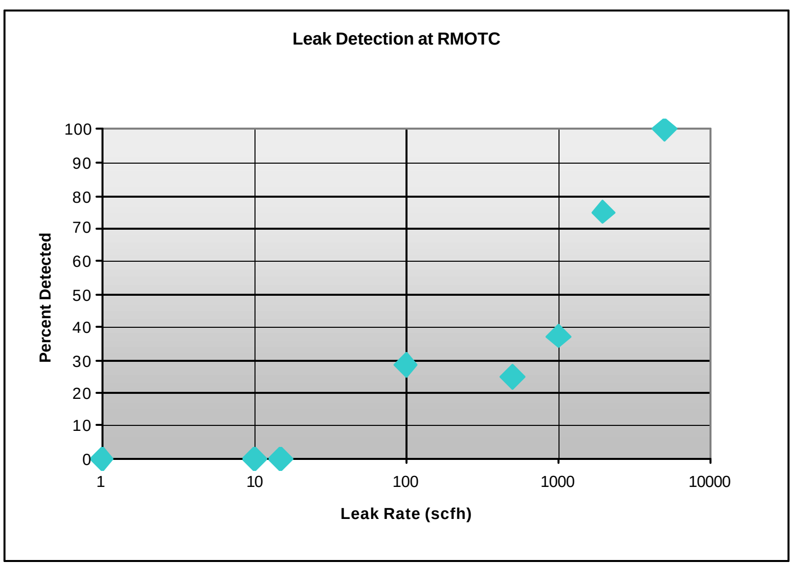

Figure 22. ANGEL System leak detection summary for RMOTC Field Test, Sept. 14-17

Leaks 2A, 2B, 2C, 2D, 2E and P5 were created by burying gas cylinders along the virtual pipeline route. Due to the limited supply of gas for these leak sites, the leaks created at these sites by the test organizers were all small 15 scfh or smaller. The prototype ANGEL system did not detect any of these small leaks throughout the course of the week. One important fact to remember with all optical remote gas detection systems is that the these systems “see” the plume of gas in the air and the size of the plume is affected by a variety of factors beyond just simple leak. Factors such as wind speed, surface roughness, diameter of the leak as it exits the ground, and atmospheric stability can all have a major effect on the size, shape and geometry of the gas plume. Leaks at sites P2 and P3 were not detected during the week due to their small size and the more diffuse plumes created by side-bore method of simulating leaks. The ANGEL system was much more successful in detecting the medium to large leaks created by tapping into the RMOTC pipeline network. Throughout the week, leaks were detected at sites 1,3,4, 5, 6, P1, and P4. The large 5,000 scfh leak at site 5 was detected and imaged on every day it was in operation.

The sensitivity of the ANGEL system reflects its prototype status. As one can see from Figure 22, the system reliably detected methane releases between 2,000 and 5,000 scfh. As the release leak size decreased, the system detectors experienced two issues. First, the methane concentrations of the medium leaks were approaching detector threshold sensitivity. The system was therefore unable to detect releases below 100 scfh. Second, the amount of background noise made analysis difficult when the release size dipped below approximately 1,200 scfh. Background noise levels coupled with low levels of target methane contributed to a fairly large number of false positives reported by the team.

One major factor contributing to the background noise and high number of false alarms was discovered in the weeks following RMOTC. Several weeks after RMOTC it was discovered that the lasers at range were misaligned and at a range of 1,000 feet the methane laser and the off-line lasers were offset by several inches. In areas of the virtual test range where surface material varied greatly in reflectivity it was possible to hit a non-reflective material with the methane laser while hitting a more reflective material with the off-line. This resulted in a spuriously high methane value at that position leading to a large number of false positive calls in some areas of the pipeline route.

One major advantage of our system was our ability to precisely point our system from the air. As a result we were able to fly over the same route numerous times over the course of the day use GIS to efficiently merge data from many individual runs. This proved to be a very effective way to effectively improve our signal to noise. By combining the information of many different runs ANGEL System analysts were able to compensate for the low laser power and poor signal to noise characteristics in the early stages of flight testing. Following adjustments to the system after RMTOC the ANGEL system was able to significantly improve the signal to noise ratio and no longer required multiple and intense GIS processing to detect leaks.

Since the RMOTC trials, the ITT Industries team has focused on addressing sensitivity and robustness issues. The system has been reconfigured to provide more laser power and higher degree of frequency lock. Beam overlap has also been greatly improved. Furthermore, our analysts are continually developing enhanced data filtering algorithms (numeric and spatial), which has helped reduce data noise, and improved our methane concentration detection threshold

2.5 Conclusions

ITT Industries Space Systems was pleased to participate in the DOE/DOT facilitated Demonstration of Remote Gas Leak Detection Systems at RMOTC. The tests conducted at RMOTC from September 13th to September 17th 2004 provided a unique opportunity to demonstrate the capabilities, value, and challenges of an airborne natural gas detection system. In spite of known performance limitations of our prototype system, the ITT ANGEL System has successfully demonstrated its ability to fly, point, scan, detect, quantify, geo-locate and ultimately provide comprehensive visualization of pipeline gas emissions in a rugged natural environment.

During each flight, the ANGEL System successfully ingested GPS/GIS data, accurately pointed at the virtual pipeline route, fully scanned the ROW (100% coverage), and collected all necessary differential GPS information to precisely locate leak locations. The Ground Data Processing systems processed all the raw data to "image" gas emissions and geo-positioned the data.

Despite the relatively windy conditions experienced during testing, the ANGEL Sensor successfully detected more than half the leaks of 500 scfh and higher. Ongoing improvements in the hardware and software will greatly improve performance of the system in the upcoming weeks readying it for commercial use in 2006. These included the ability to efficiently detect, quantify, geo-locate and image natural gas leak plumes from the air. During this demonstration the ANGEL team learned a number of very valuable lessons.

- We validated the concept of using Differential Absorption Lidar (DIAL) for gas leak detection and quantification from a fixed wing aircraft. Integration of the sensor into the test aircraft was completed at the Casper Airport. The first fully integrated ANGEL DIAL data ever collected was on 14 September 2004, the second day of the RMOTC test.
- We confirmed that the ANGEL Intelligent Pointing and Scanning System allowed the aircraft to fly the Virtual Pipeline end-to-end at high speed and inspect 100% of the pipeline on a single pass. The ability to collect data accurately, rapidly, and efficiently is critical to future commercial operations.
- We challenged the Beta version of our ground data processing software and it worked well throughout the week. The experience of having to rapidly process vast quantities of data during the demonstration is currently driving major improvements in the area of automated data processing and analysis.
- We verified the relationship between laser output power and our ability to detect leaks. This was one of the most important lessons learned at RMOTC. Increasing laser power greatly improves our ability to lock on a set wavelength and greatly improves the signal to noise ratio of the data. On Monday of the test, the ANGEL team more than doubled sensor laser power output by replacing a damaged optic and further hardware improvements are continuing.

2.5.1 Post RMOTC flight testing

Immediately after participation in the RMOTC exercise, the simulated leaks at Pendleton Tap were re-flown. During this effort, simulated calibration leaks were flown a total of 8 separate times in wind speeds which ranged from 0 mph to speeds of up to 14 mph. Results from a single overflight are shown in Figure 23. Results from all 8 runs are shown in Figure 24. During these runs the leak rate ranged from 3,500 to 4,680 scfh. Most notable was the major effect of the wind. As predicted by the gas plume modeling, gas tends to "pool" near the leak under light wind conditions. Winds greater than 10 mph tend to rapidly disperse the leaking gas and result in plumes that are very chopped up and hard to detect.

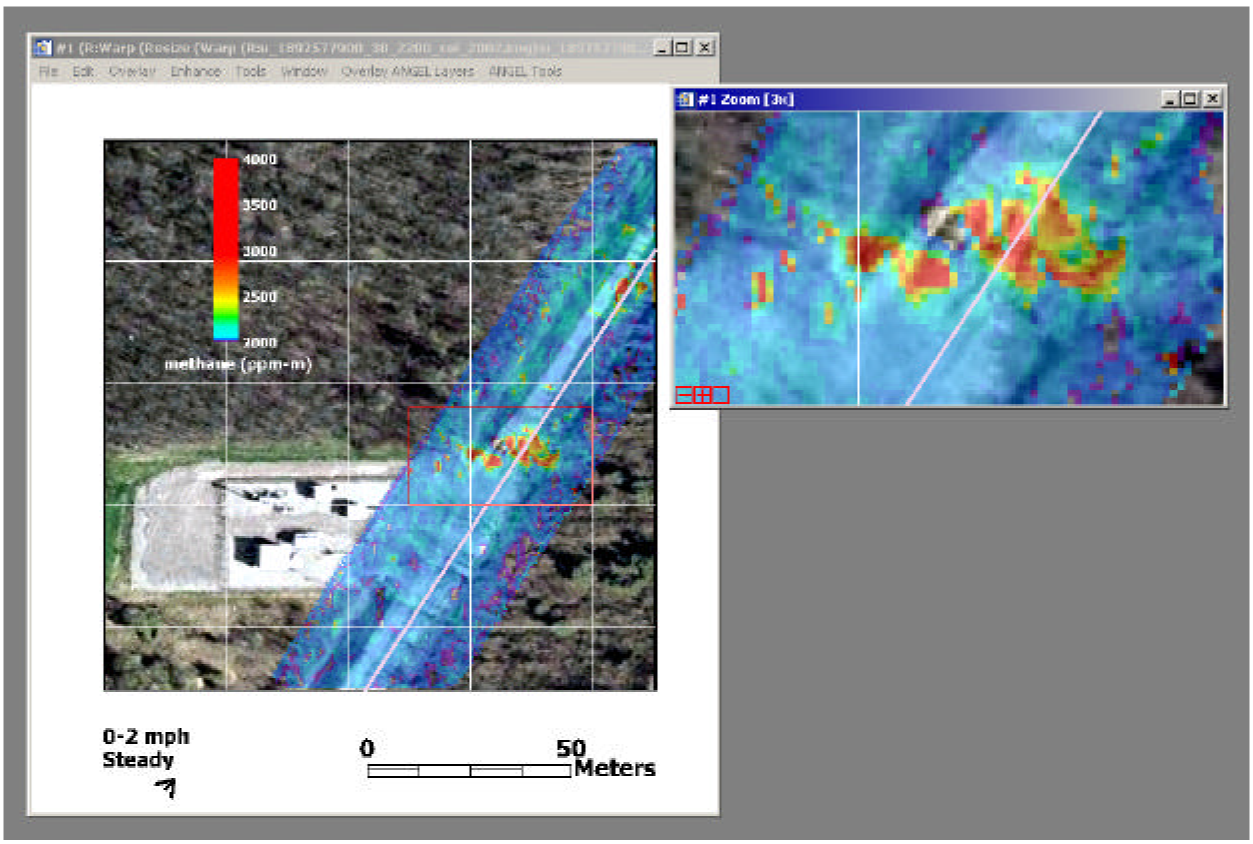

Figure 23. ANGEL DIAL system image of a gas plume from a 3,500 scfh methane release along a tree-lined pipeline right-of-way near Buffalo, NY. This data was in October, 2004 from the TIFS test aircraft flying at 150 mph from a height of 1,000 feet above the ground. This simulated leak was created in cooperation with National Fuel near the Pendleton Meter Station.

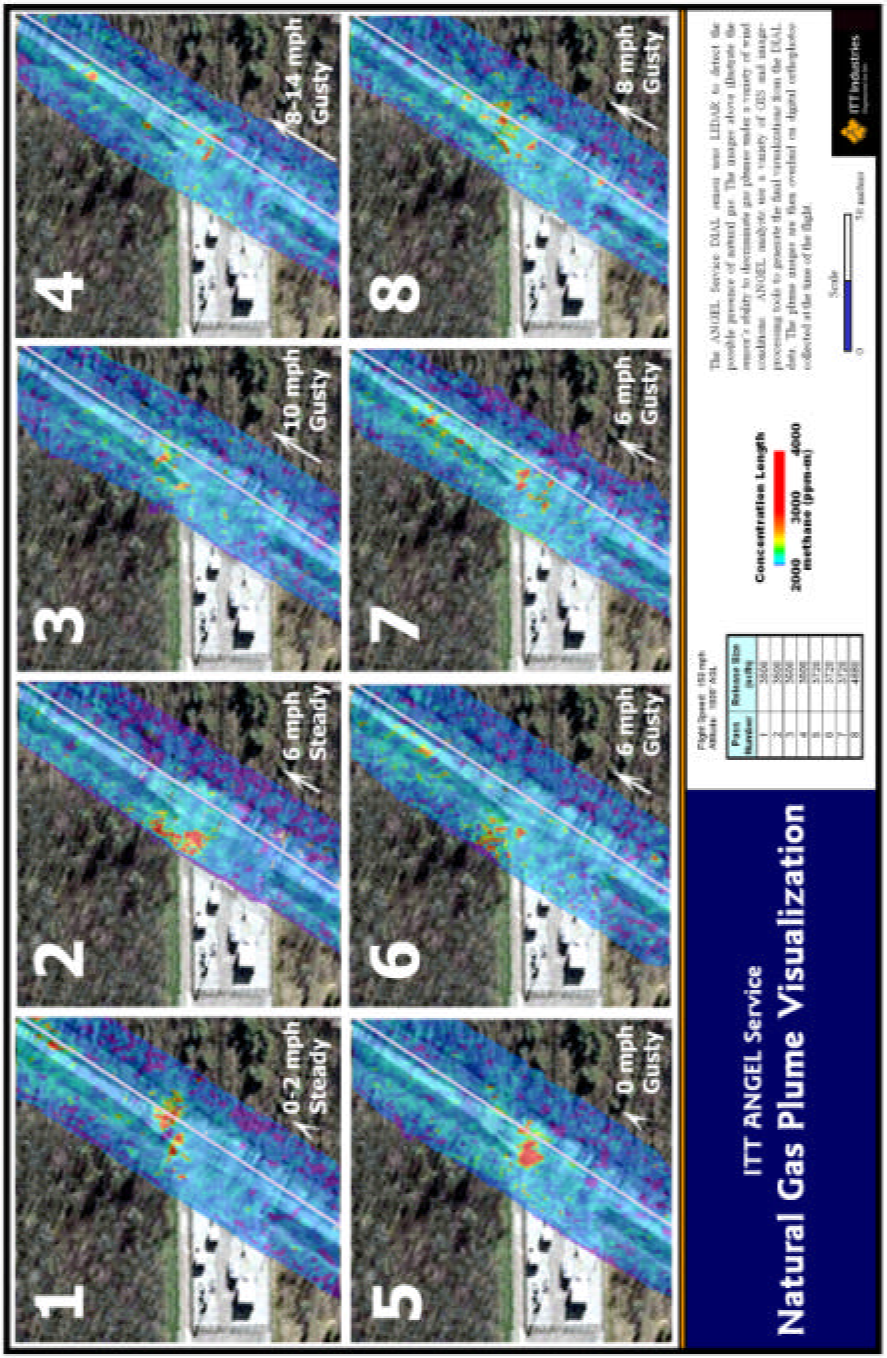

Figure 24. Eight separate ANGEL DIAL system images of a gas plume from a 3,500 scfh methane release along a tree-lined pipeline right-of-way near Buffalo, NY. This data was collected in October, 2004 from the TIFS test aircraft flying at 150 mph from a height of 1,000 feet above the ground. These simulated leaks were created in cooperation with National Fuel near the Pendleton Meter Station. These images indicate that lower wind speeds at ground level allow the accumulation of higher concentrations of gas. These images were collected over a

2.5.2 Qualitative Comments on ANGEL Technology

The ANGEL technology demonstrated at RMOTC proved to be enormously productive. Flying at over 130 Knots, the test aircraft was able to fully inspect the relatively short 7.5 mile Virtual Pipeline route in roughly 4.5 minutes. As a result, we were able to collect 7 complete inspections of the RMOTC Virtual Pipeline in our allotted 50-minute window. Productivity would have been even greater if the aircraft didn't have to circle back after each 7.5 mile pipeline pass. During pre-RMOTC ground tests, ANGEL laser power levels were less than 50% of specification. Modeling of expected sensor performance given these output levels predicted that ANGEL would be able to confidently detect leaks of roughly 1000 scfh. Upon receipt of the actual size and position of the leaks from SWRI, we demonstrated our ability to detect and image a number of leaks of 100 scfh or larger despite the relatively high wind conditions experienced at RMOTC.

While the ANGEL system demonstrated at RMOTC is at an early stage of development, data collection of this quality at this stage is extremely encouraging.

Initial data analysis focused on the spatial aspects of multiple collections in a single day. Data from multiple passes improved our confidence in our ability to interpret ANGEL data and detect leaks. Recent algorithmic improvements (since the submission of the final report to DOE) now allow better leak identification with the data from a single pass. Over the next few months, sensor hardware upgrades will allow confident detection of appreciably smaller leaks. Integration of the ethane laser bench (not used at RMOTC) combined with improvements in signal-to-noise ratio will result in significant sensor system performance.

Custom software designed to process the ANGEL data and display an image of a gas plume worked extremely well from the first day of the demonstration, and this software was continuously improved over the course of the week. Subsequent improvements in determining the exact position of "laser spots" on the ground now allow us to more accurately display the size and shape of natural gas plumes.

Our understanding of the phenomenology of DIAL gas leak detection has been greatly improved by our participation in the DOE/DOT sponsored field test. Over the course of the week we imaged gas leak plumes of various sizes and shapes literally hundreds of times. The data collected during our time in Wyoming has been invaluable for gaining a better understanding gas leak behavior under a range of conditions.

3.0 Acknowledgements

The authors would like to acknowledge of numerous members of the ITT Space Systems Division Engineering and Business Staff. In particular, we would like to acknowledge the contributions of the following individuals who's dedication and expertise made this work possible: Steve Bauer, Paul Blaszkowiak, Janice Brooks, Dan Brake, Charles Cacciato, Mark Carducci, Mike Clayton, Mike Crowder, Tim Cutler, Rita Hasenauer, Mark Janosky, Hooshmand Kalayeh, Joseph Lippert, Norm Lopez, Lisa McConnell, Wendy Minotti, Craig Oswald, Brian Nagy, Roger Pawlowski, Matt Severski, Gene Wess, John Winterberger, Gregg Wright. We would also like to acknowledge the contributions of the following organizations: Coherent Technologies Inc., Critical Link, General Dynamics, and PhilCon.

4.0 Graphical Material

List of Figures

List of Tables

5.0 References

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7.0 List of Acronyms and Abbreviations

AGCS	Active Gas Correlation Spectroscopy
AGL	Above Ground Level
ANGEL	Airborne Natural Gas Emission Lidar
APVIAS	ANGEL Pipeline Visual Inspection and Analysis Software
BAGI	Backscatter Absorption Gas Imaging
CPL	Concentration Path Length
DIAL	Differential Absorption Lidar
DOE	Department of Energy
DOT	Department of Transportation
GCS	Gas Correlation Spectroscopy
GDP	Ground Data Processing
GIS	Geographic Information Systems
GPS	Global Positioning System
HIS	Hyperspectral Imaging
LIDAR	Light Detection and Ranging
mph	miles per hour
NETL	National Energy Technology Laboratory
nm	nanometers
OPS	Office of Pipeline Safety
RMOTC	Rocky Mountain Oilfield Testing Center
ROW	Right of Way
scfh	standard cubic feet per hour
SNR	Signal to Noise Ratio
tcf	Trillion cubic feet
TIFS	Total In-Flight Simulator

Attachment 1: ITT Equipment Provider Test Report

ANGEL Service Customer Report

Rocky Mountain Oilfield Testing Center (RMOTC) Virtual Pipeline Inspection

DATE(s) INSPECTION DATA ACQUIRED:

September 14,2004

CONTRACT NUMBER:

DOE/National Energy Technology Laboratory Cooperative Development Agreement # DE-FC26-03NT41877

IN RESPONSE TO RFP:

DOE Program Solicitation (PS) No. DE-PS26-02NT41613

SUBMITTED BY:

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San Antonio, Texas

ITT Industries
Engineered for life

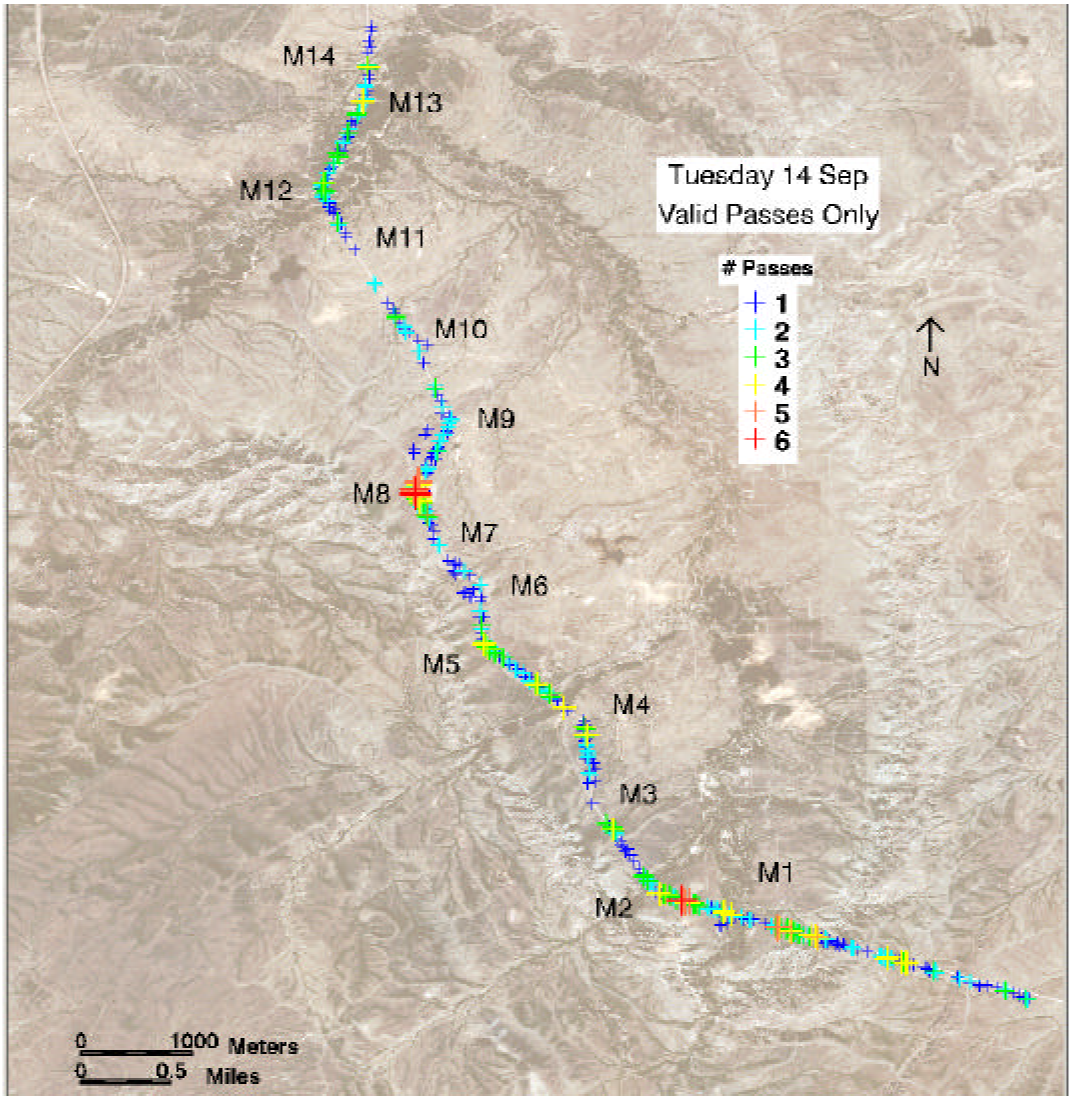
REPORT DATE:

October 8, 2004

Executive Summary:

On September 14, 2004 we flew the route identified as "RMOTC Virtual Pipeline" with the ITT Industries ANGEL Sensor. This route was flown multiple times to ensure we had fully covered the complete Virtual Pipeline Route and to provide increased sample density to improve detection of smaller emissions. Analysis of the information collected indicates a number of areas of significant methane concentration along the pipeline right of way. The locations and relative size/concentration patterns for these are described in detail in this report.

The route flown is depicted below. All detected concentration areas are labeled with crosses. Color-coding is used to indicate detection of the methane concentration on multiple passes, with red indicating that the specific methane concentration was detected (within 30 meters) on five separate passes. Eleven distinct methane concentration areas were detected with sufficient quantity and frequency (5 or 6 passes) that they are high confidence. Elevated concentrations of methane in the area of a 1,000 scfh calibration leak near M1 were detected 4 times throughout the day.



Methane Detections

The methane emissions with the highest confidence were captured on a relatively large number of passes as indicated in this table. The geographic coordinates provide the location of the aggregated multiple detections.

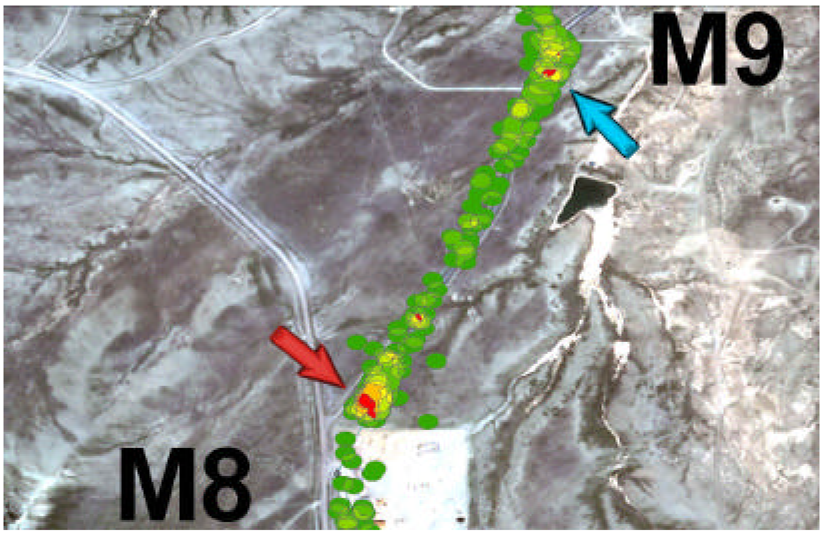
NAD 27 Data (DMS)						
Latitude	Longitude	Leak Detection	Date	AM Passes	PM Passes	Comments
43 14 57.966	-106 11 27.3228	6	09/14/04	3	1,2,3,4,6	south of M2
43 14 58.992	-106 11 31.6464	5	09/14/04	3	2,3,4,7	M1-M2
43 15 0.0216	-106 11 35.0844	5	09/14/04	3	2,3,4,7	south of M2
43 15 1.0188	-106 11 37.7412	5	09/14/04	3	2,3,4,7	vicinity of M2
43 16 39.8244	-106 12 50.6232	5	09/14/04	3,4	1,2,7	vicinity of M5
43 17 45.3624	-106 13 15.4164	6	09/14/04	3	1,2,4,6,7	already have M8 (gas plant)
43 18 6.048	-106 13 4.1844	5	09/14/04	3,4	1,2,7	vicinity of M9
43 18 57.0096	-106 13 30.9792	5	09/14/04		2,3,4,6,7	south of M11
43 19 37.128	-106 13 53.7888	5	09/14/04	3,4	1,3,7	many discrete points just south of M12
43 19 40.0908	-106 13 53.7852	6	09/14/04	3,4	1,2,3,4	just north of M12
43 19 51.2508	-106 13 48.5724	5	09/14/04	3	2,4,6,7	single small area M12-M13

Methane emissions detected with lesser, but still significant confidence are listed in the table below. In all cases these were detected on multiple passes as well, but not as consistently as the detections documented above.

NAD 27 Data (DMS)			
Latitude	Longitude	Date	Comments
43 19 54.7284	-106 13 47.3628	14-Sep-04	M12-M13
43 15 25.2	-106 11 58.9632	14-Sep-04	M2-M3
43 16 14.304	-106 12 17.406	14-Sep-04	M4-M5
43 17 28.8132	-106 13 12.5976	14-Sep-04	M8 - south of gas plant
43 17 45.7188	-106 13 15.3012	14-Sep-04	M8 (gas plant)
43 19 40.08	-106 13 53.778	14-Sep-04	just north of M12
43 14 57.9336	-106 11 27.3732	14-Sep-04	north of M1
43 18 56.826	-106 13 30.6768	14-Sep-04	south of M11
43 14 59.964	-106 11 35.2896	14-Sep-04	south of M2
43 15 1.0728	-106 11 38.3712	14-Sep-04	vicinity of M2
43 15 5.5764	-106 11 45.0348	14-Sep-04	just north of M2
43 16 23.0772	-106 12 29.3076	14-Sep-04	north of M4-M5
43 14 59.0316	-106 11 31.704	14-Sep-04	north of M1
43 19 51.0384	-106 13 48.5292	14-Sep-04	single small area M12-M13
43 19 37.2	-106 13 53.7888	14-Sep-04	just south of M12
43 19 31.6884	-106 13 50.8584	14-Sep-04	many discrete points south of M12
43 20 8.0916	-106 13 40.4868	14-Sep-04	south of M13
43 16 49.8504	-106 12 51.5232	14-Sep-04	south of M6
43 14 53.9196	-106 11 14.2692	14-Sep-04	vicinity of M1
43 16 39.954	-106 12 50.5296	14-Sep-04	vicinity of M5
43 18 6.246	-106 13 4.044	14-Sep-04	vicinity of M9

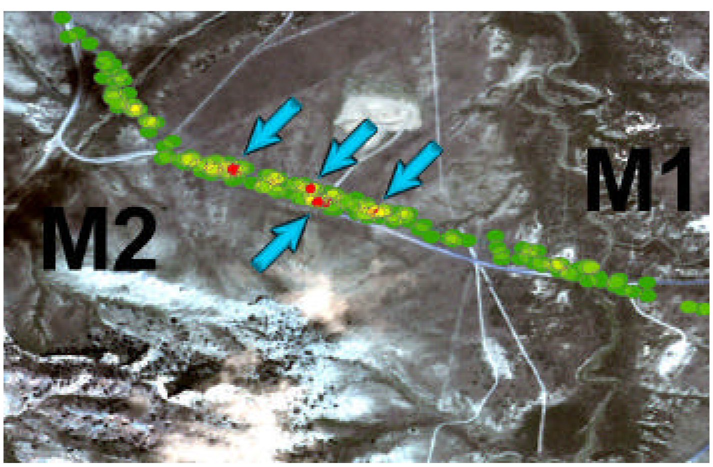
Significant Emissions

In this survey there are several areas that stand out due to the size and concentration-pathlength values of methane plume and frequency of detection. These are identified in the images provided below with red and orange plume position markers. The green markers are areas where there were potential indicators for methane but these were only detected on single passes. These do not represent highly significant indicators.



- N 43 18 6.048
- W -106 13 4.1844
- Detected on 5 passes
- Vicinity of M9

- N 43 17 45.3624
- W -106 13 15.4164
- Detected on 6 passes
- Area North of Gas Plant
- Note 2nd possible area (without arrow) to the NE

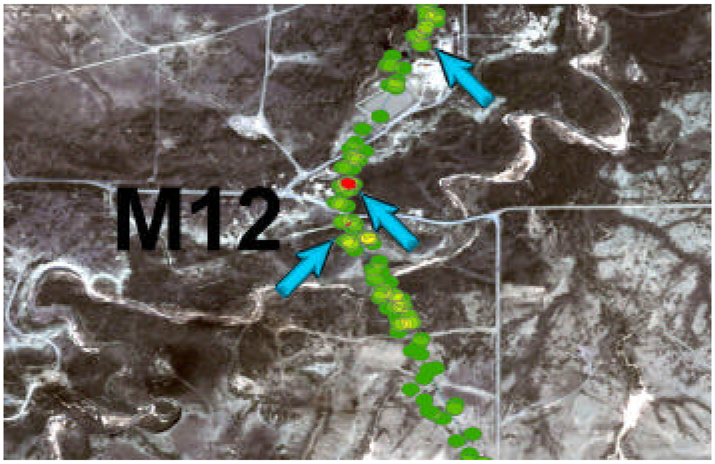


- N 43 14 57.966
- W -106 11 27.3228
- Detected on 6 passes
- South of M2

- N 43 14 58.992
- W -106 11 31.6464
- Detected on 5 passes

- N 43 15 0.0216
- W -106 11 35.0844
- Detected on 5 passes

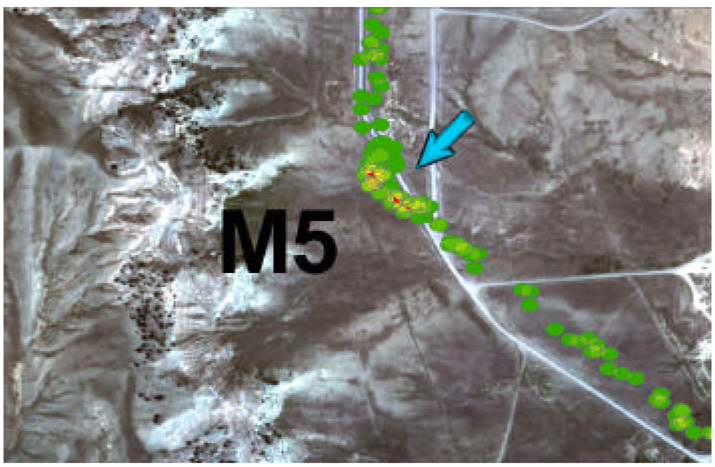
- N 43 15 1.0188
- W -106 11 37.7412
- Detected on 5 passes



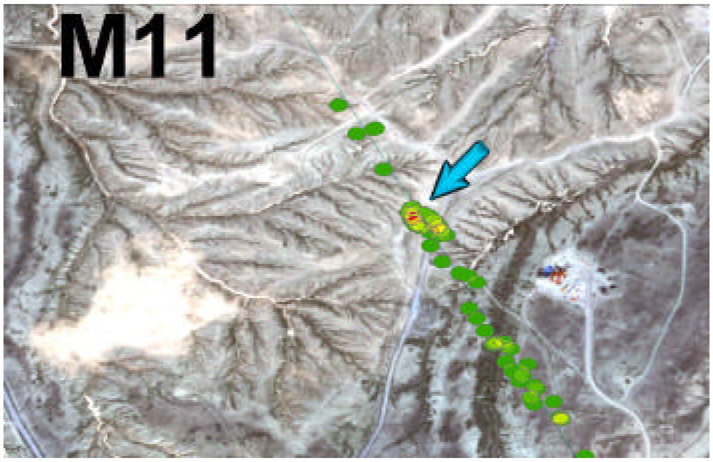
- N 43 19 51.2508
- W -106 13 48.5724
- Detected on 5 passes

- N 43 19 40.0908
- W -106 13 53.7852
- Detected on 6 passes
- Just north of M12

- N 43 19 37.128
- W -106 13 53.7888
- Detected on 5 passes



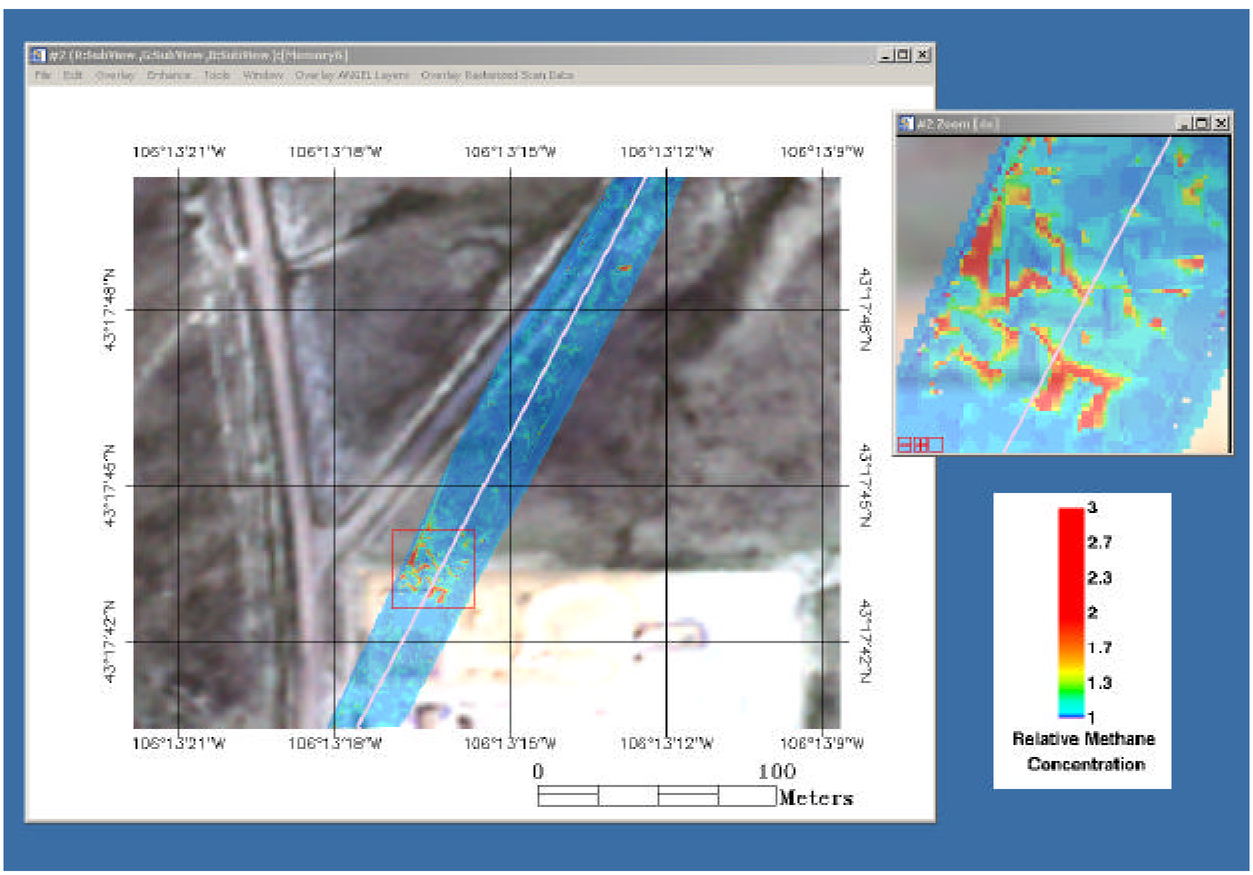
- N 43 16 39.8244
- W -106 12 50.6232
- Detected on 5 passes
- Vicinity of M5



- N 43 18 57.0096
- W -106 13 30.9792
- Detected on 5 passes
- South of M11

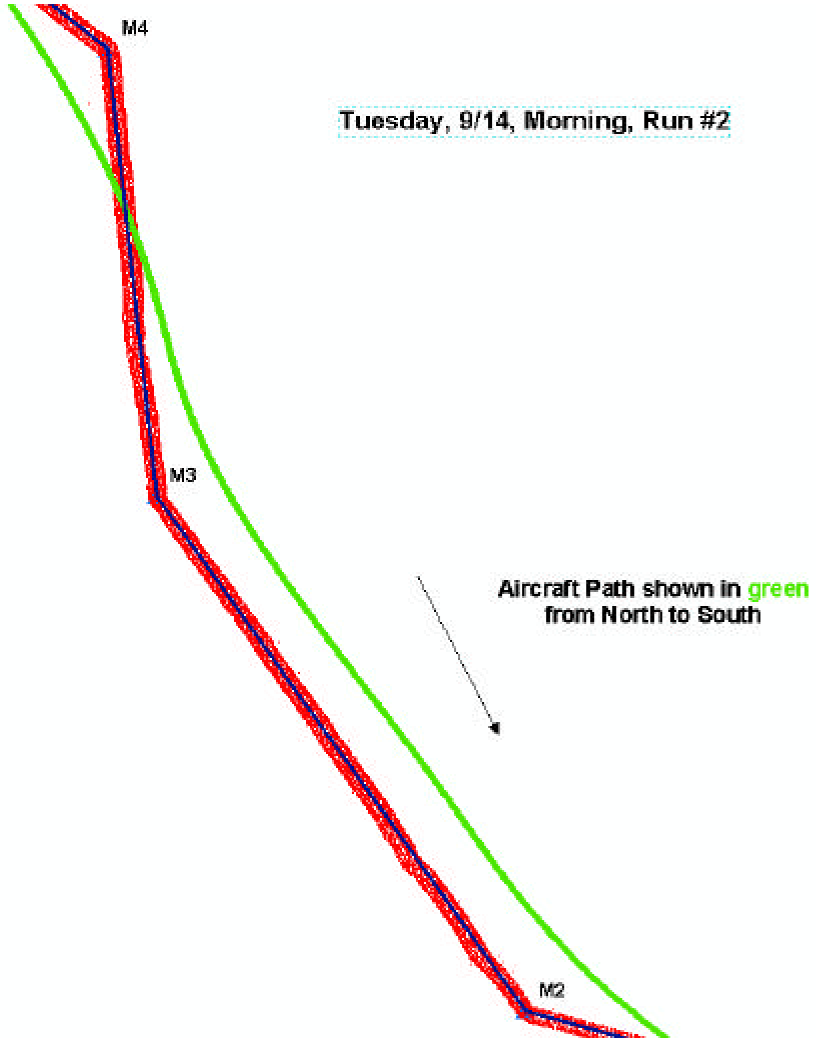
Special Case Analysis

From the collection on Tuesday, September 14, 2004 one location north of M8 stood out above all the others and warranted additional analysis. A raster-based analysis and methane images of the area north of the RMOTC Gas Plant area and an area of significant emission are shown below. This is the methane image map from pass 4 on the AM of Tuesday, September 14th, 2004.



Right of Way Coverage

ANGEL collection planning starts with developing a flight plan that will place the aircraft over the pipeline route. In most cases the aircraft flight path cannot perfectly match the pipeline route but the ANGEL sensor can still track the full right of way. This is important to ensure that we provide adequate collection coverage of the full right of way for the entire length of the pipeline segment being surveyed. As the aircraft then flies the designated route, the sensor tracks and images the actual right of way, even when not directly under the aircraft and regardless of minor flight variations. The information collected from each flight is analyzed to determine that the right of way was fully covered as planned. The graphic below shows the actual results from a small segment of one such flight path over the designated pipeline route. The green line is the path of the aircraft and the red band is made up of all the individual sensor collects throughout the flight. In this case the sensor accurately tracked the pipeline and provided full coverage of the right of way. This post flight analysis provides confidence that we have adequately covered the pipeline path and right-of-way for the full 7.5-mile length of the survey.

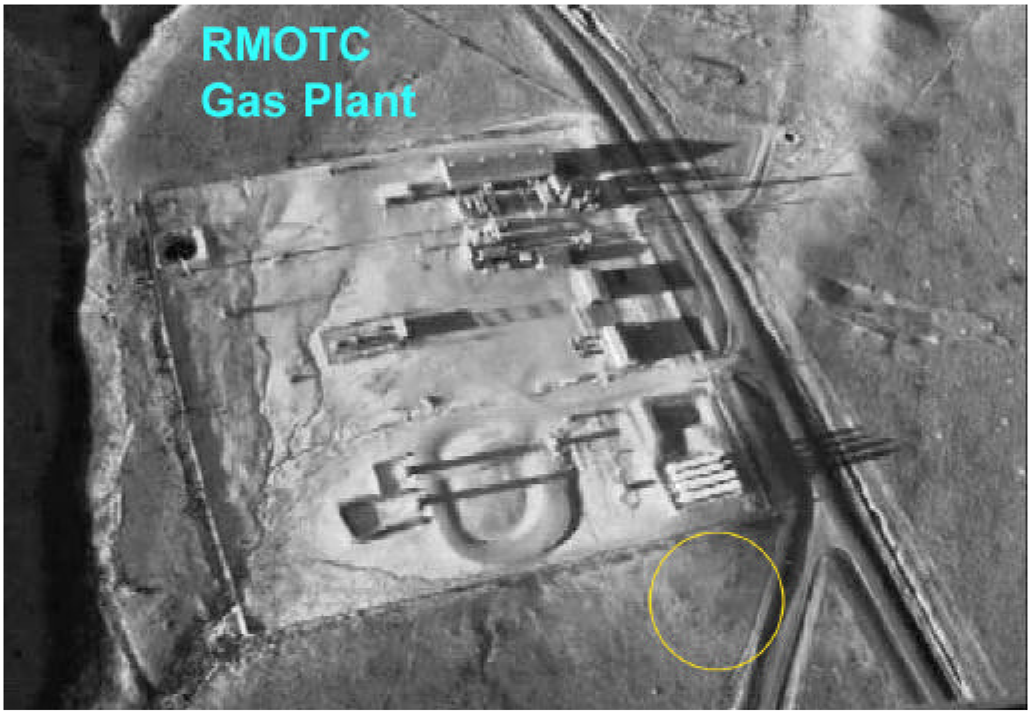


Flight Path Verification

The base imagery for this analysis is from Quickbird multispectral collection provided by DOE/NETL. The methane concentration pathlengths were measured from a single pass (4th flight on the morning of September 14, 2004) and the colors represent the relative concentration pathlength of methane within the ANGEL swath. Normal background methane levels are shown in dark blue. ANGEL collector scan swath is approximately 25 meters wide and is superimposed on the base image. Elevated concentrations of methane clearly stand out in red and the highest concentrations are located north of the Gas Plant (north of location M8 on the Virtual Pipeline route). It should be noted that the imagery used as purchased was not perfectly geo-registered and is provided to give approximate context (+/- 15 meters) to the ANGEL analysis data, not absolute positioning.

If no satellite or aerial photography imagery is available for a survey, the ANGEL aircraft has been fitted with a monochrome video camera that is used for flight path verification. This camera collects looking forward at 15 degrees from nadir and provides MPEG2 motion video imagery with approximately 1.4 ft raw GSD resolution. A sample frame is shown below. The video camera currently in use was designed only to provide engineering flight test information and will soon be replaced with a much higher resolution color and false color IR digital camera designed to collect a continuous strip of geo-referenced imagery as the sensor is flown along the pipeline right-of-way.

The ANGEL aircraft image below shows the RMOTC Gas Plant viewed from the North during one of the early morning passes. The yellow circle indicates the approximate location of the elevated levels of methane seen throughout the day in the Northwest corner of the Gas Plant.



Attachment 2: ITT ANGEL Customer Report – 14 Sept 2004 Collection

ANGEL Service Customer Report

Rocky Mountain Oilfield Testing Center (RMOTC) Virtual Pipeline Inspection

DATE(s) INSPECTION DATA ACQUIRED:

September 14,2004

CONTRACT NUMBER:

DOE/National Energy Technology Laboratory Cooperative Development Agreement # DE-FC26-03NT41877

IN RESPONSE TO RFP:

DOE Program Solicitation (PS) No. DE-PS26-02NT41613

SUBMITTED BY:

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SUBMITTED TO:

Chris Buckingham
Southwest Research Labs
6220 Culebra Road (78238-5166)
P.O. Drawer 28510 (78228-0510)
San Antonio, Texas

REPORT DATE:

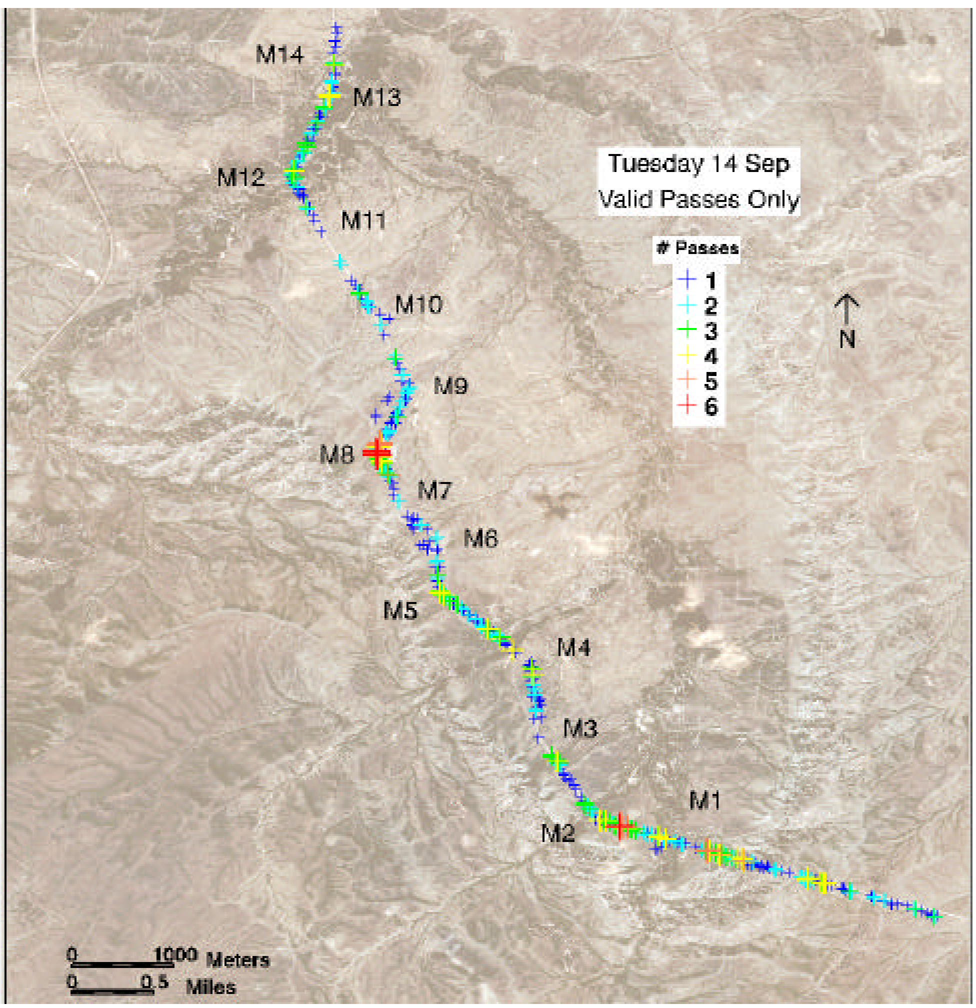
October 8, 2004

ITT Industries
Engineered for life

Executive Summary:

On September 14, 2004 we flew the route identified as "RMOTC Virtual Pipeline" with the ITT Industries ANGEL Sensor. This route was flown multiple times to ensure we had fully covered the complete Virtual Pipeline Route and to provide increased sample density to improve detection of smaller emissions. Analysis of the information collected indicates a number of areas of significant methane concentration along the pipeline right of way. The locations and relative size/concentration patterns for these are described in detail in this report.

The route flown is depicted below. All detected concentration areas are labeled with crosses. Color-coding is used to indicate detection of the methane concentration on multiple passes, with red indicating that the specific methane concentration was detected (within 30 meters) on five separate passes. Eleven distinct methane concentration areas were detected with sufficient quantity and frequency (5 or 6 passes) that they are high confidence. Elevated concentrations of methane in the area of a 1,000 scfh calibration leak near M1 were detected 4 times throughout the day.



Methane Detections

The methane emissions with the highest confidence were captured on a relatively large number of passes as indicated in this table. The geographic coordinates provide the location of the aggregated multiple detections.

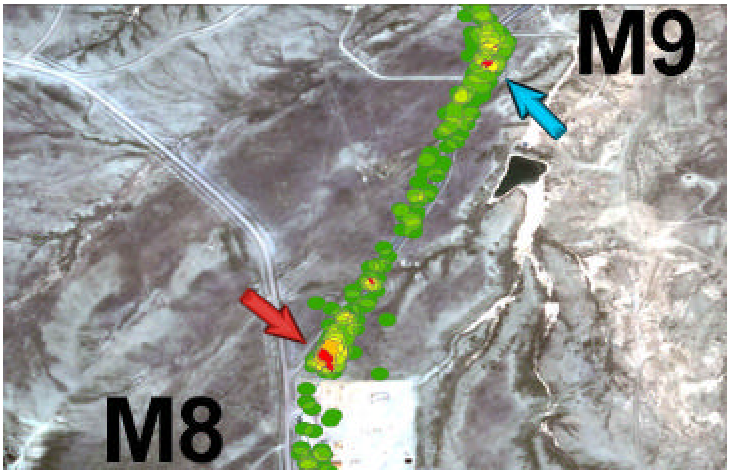
NAD 27 Data (DMS)						
Latitude	**Longitude**	**Leak Detection**	**Date**	**AM Passes**	**PM Passes**	**Comments**
43 14 57.966	-106 11 27.3228	6	09/14/04	3	1,2,3,4,6	south of M2
43 14 58.992	-106 11 31.6464	5	09/14/04	3	2,3,4,7	M1-M2
43 15 0.0216	-106 11 35.0844	5	09/14/04	3	2,3,4,7	south of M2
43 15 1.0188	-106 11 37.7412	5	09/14/04	3	2,3,4,7	vicinity of M2
43 16 39.8244	-106 12 50.6232	5	09/14/04	3,4	1,2,7	vicinity of M5
43 17 45.3624	-106 13 15.4164	6	09/14/04	3	1,2,4,6,7	already have M8 (gas plant)
43 18 6.048	-106 13 4.1844	5	09/14/04	3,4	1,2,7	vicinity of M9
43 18 57.0096	-106 13 30.9792	5	09/14/04		2,3,4,6,7	south of M11
43 19 37.128	-106 13 53.7888	5	09/14/04	3,4	1,3,7	many discrete points just south of M12
43 19 40.0908	-106 13 53.7852	6	09/14/04	3,4	1,2,3,4	just north of M12
43 19 51.2508	-106 13 48.5724	5	09/14/04	3	2,4,6,7	single small area M12-M13

Methane emissions detected with lesser, but still significant confidence are listed in the table below. In all cases these were detected on multiple passes as well, but not as consistently as the detections documented above.

NAD 27 Data (DMS)			
Latitude	**Longitude**	**Date**	**Comments**
43 19 54.7284	-106 13 47.3628	14-Sep-04	M12-M13
43 15 25.2	-106 11 58.9632	14-Sep-04	M2-M3
43 16 14.304	-106 12 17.406	14-Sep-04	M4-M5
43 17 28.8132	-106 13 12.5976	14-Sep-04	M8 - south of gas plant
43 17 45.7188	-106 13 15.3012	14-Sep-04	M8 (gas plant)
43 19 40.08	-106 13 53.778	14-Sep-04	just north of M12
43 14 57.9336	-106 11 27.3732	14-Sep-04	north of M1
43 18 56.826	-106 13 30.6768	14-Sep-04	south of M11
43 14 59.964	-106 11 35.2896	14-Sep-04	south of M2
43 15 1.0728	-106 11 38.3712	14-Sep-04	vicinity of M2
43 15 5.5764	-106 11 45.0348	14-Sep-04	just north of M2
43 16 23.0772	-106 12 29.3076	14-Sep-04	north of M4-M5
43 14 59.0316	-106 11 31.704	14-Sep-04	north of M1
43 19 51.0384	-106 13 48.5292	14-Sep-04	single small area M12-M13
43 19 37.2	-106 13 53.7888	14-Sep-04	just south of M12
43 19 31.6884	-106 13 50.8584	14-Sep-04	many discrete points south of M12
43 20 8.0916	-106 13 40.4868	14-Sep-04	south of M13
43 16 49.8504	-106 12 51.5232	14-Sep-04	south of M6
43 14 53.9196	-106 11 14.2692	14-Sep-04	vicinity of M1
43 16 39.954	-106 12 50.5296	14-Sep-04	vicinity of M5
43 18 6.246	-106 13 4.044	14-Sep-04	vicinity of M9

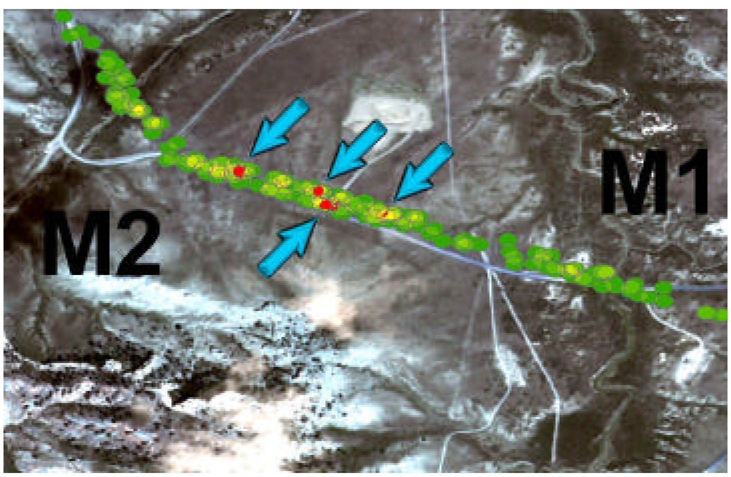
Significant Emissions

In this survey there are several areas that stand out due to the size and concentration-pathlength values of methane plume and frequency of detection. These are identified in the images provided below with red and orange plume position markers. The green markers are areas where there were potential indicators for methane but these were only detected on single passes. These do not represent highly significant indicators.



- N 43 18 6.048
- W -106 13 4.1844
- Detected on 5 passes
- Vicinity of M9

- N 43 17 45.3624
- W -106 13 15.4164
- Detected on 6 passes
- Area North of Gas Plant
- Note 2nd possible area (without arrow) to the NE

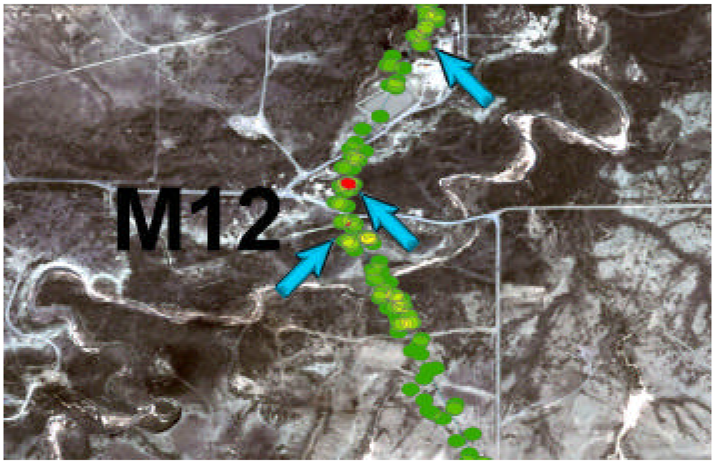


- N 43 14 57.966
- W -106 11 27.3228
- Detected on 6 passes
- South of M2

- N 43 14 58.992
- W -106 11 31.6464
- Detected on 5 passes

- N 43 15 0.0216
- W -106 11 35.0844
- Detected on 5 passes

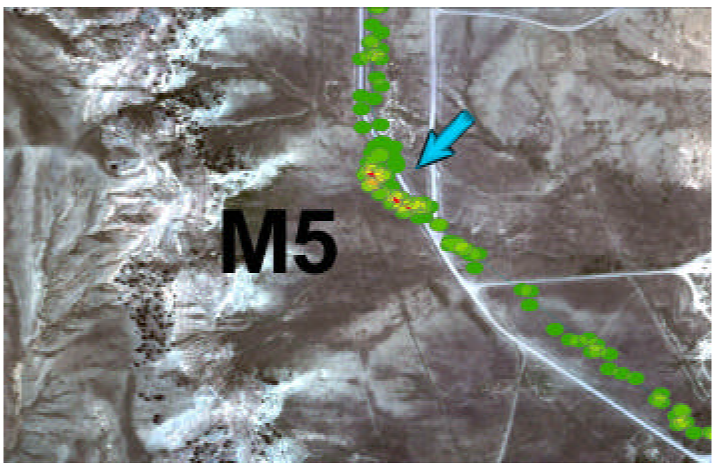
- N 43 15 1.0188
- W -106 11 37.7412
- Detected on 5 passes



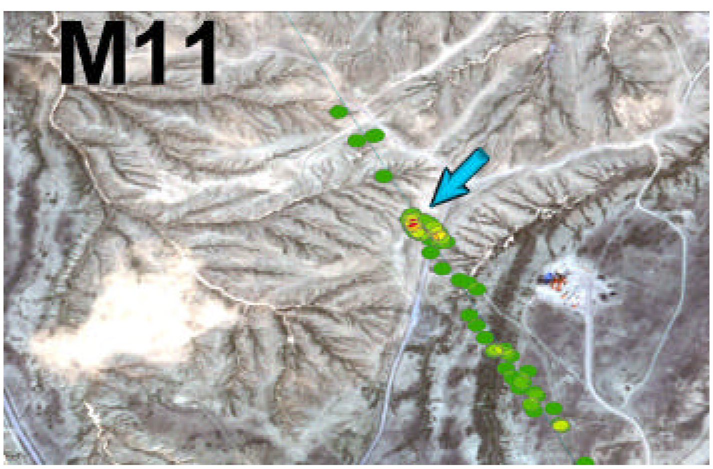
- N 43 19 51.2508
- W -106 13 48.5724
- Detected on 5 passes

- N 43 19 40.0908
- W -106 13 53.7852
- Detected on 6 passes
- Just north of M12

- N 43 19 37.128
- W -106 13 53.7888
- Detected on 5 passes



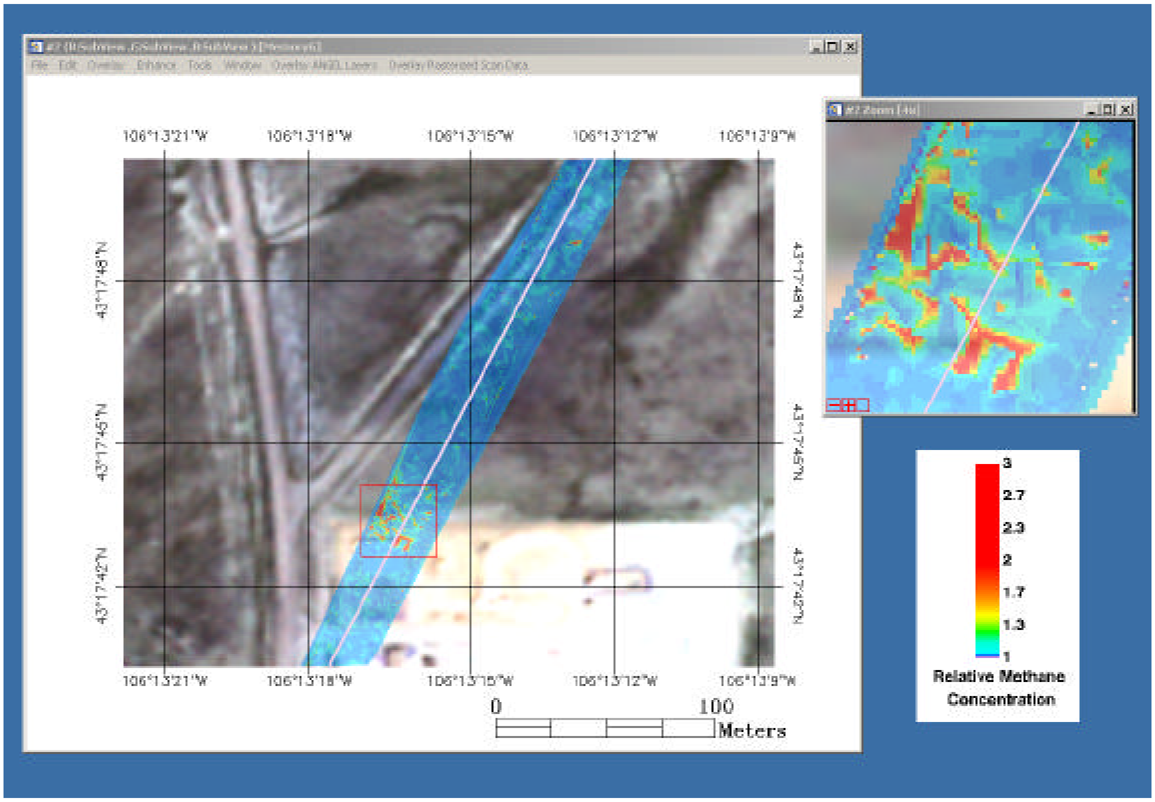
- N 43 16 39.8244
- W -106 12 50.6232
- Detected on 5 passes
- Vicinity of M5



- N 43 18 57.0096
- W -106 13 30.9792
- Detected on 5 passes
- South of M11

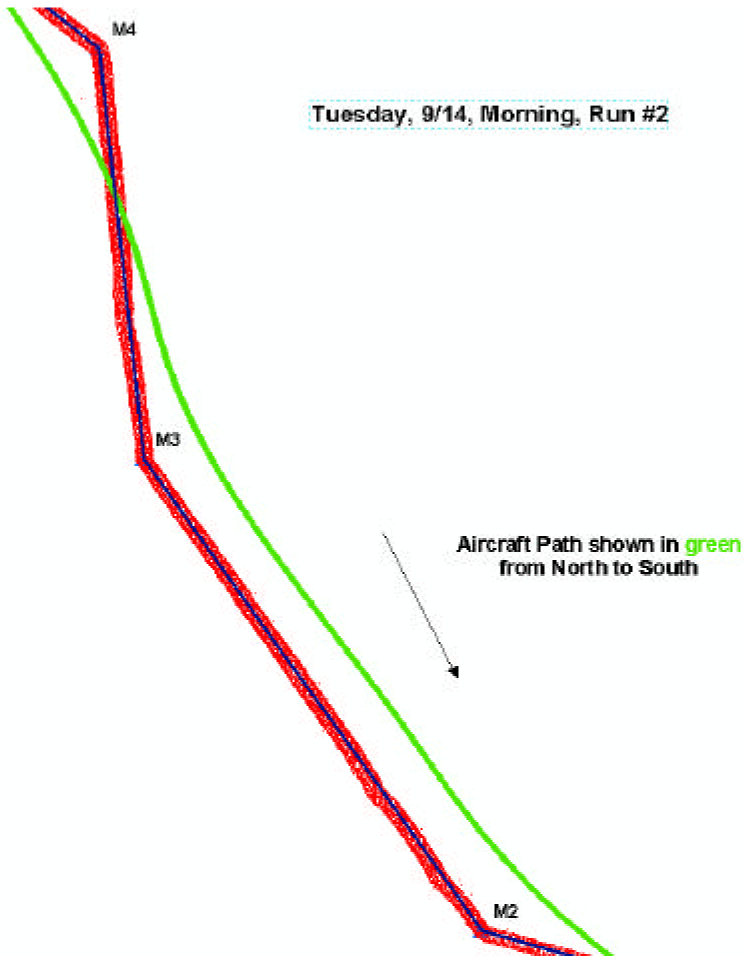
Special Case Analysis

From the collection on Tuesday, September 14, 2004 one location north of M8 stood out above all the others and warranted additional analysis. A raster-based analysis and methane images of the area north of the RMOTC Gas Plant area and an area of significant emission are shown below. This is the methane image map from pass 4 on the AM of Tuesday, September 14th, 2004.



Right of Way Coverage

ANGEL collection planning starts with developing a flight plan that will place the aircraft over the pipeline route. In most cases the aircraft flight path cannot perfectly match the pipeline route but the ANGEL sensor can still track the full right of way. This is important to ensure that we provide adequate collection coverage of the full right of way for the entire length of the pipeline segment being surveyed. As the aircraft then flies the designated route, the sensor tracks and images the actual right of way, even when not directly under the aircraft and regardless of minor flight variations. The information collected from each flight is analyzed to determine that the right of way was fully covered as planned. The graphic below shows the actual results from a small segment of one such flight path over the designated pipeline route. The green line is the path of the aircraft and the red band is made up of all the individual sensor collects throughout the flight. In this case the sensor accurately tracked the pipeline and provided full coverage of the right of way. This post flight analysis provides confidence that we have adequately covered the pipeline path and right-of-way for the full 7.5-mile length of the survey.

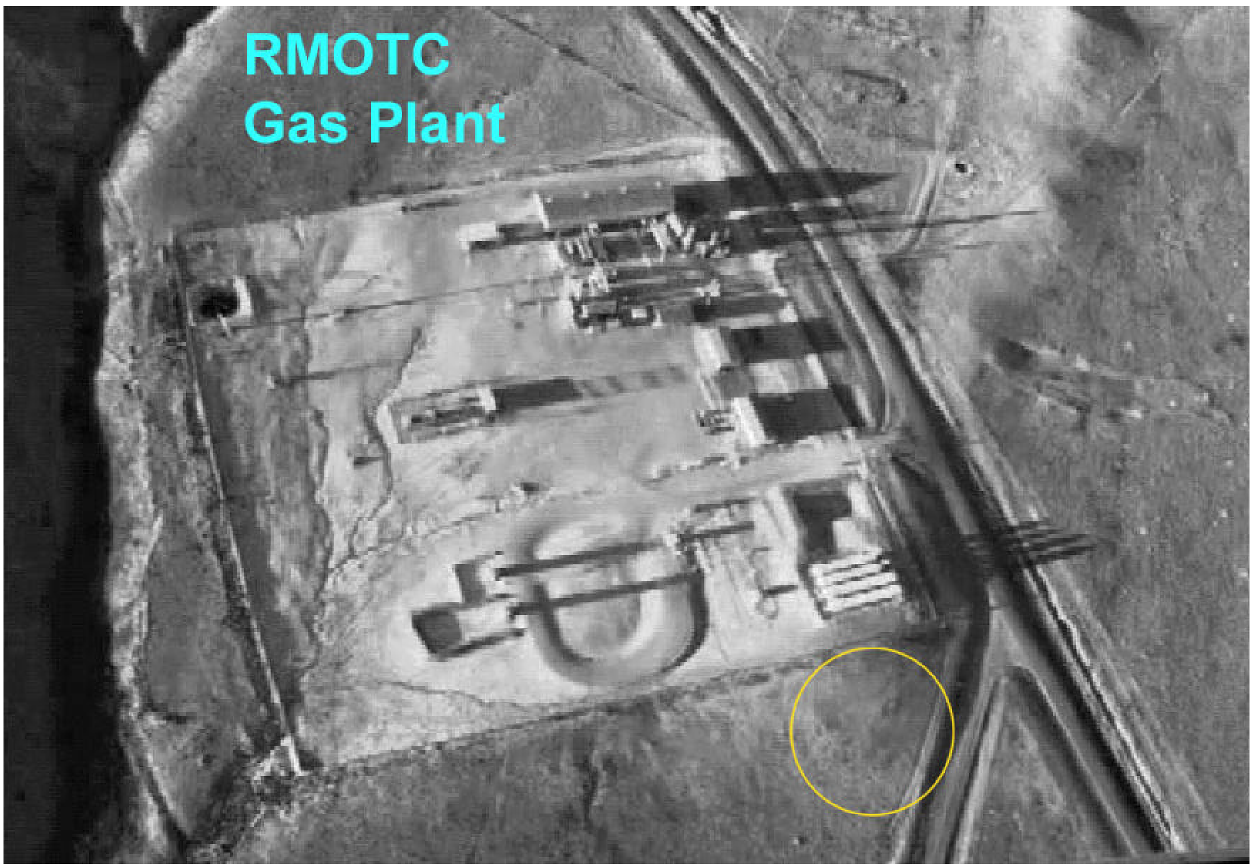


Flight Path Verification

The base imagery for this analysis is from Quickbird multispectral collection provided by DOE/NETL. The methane concentration pathlengths were measured from a single pass (4th flight on the morning of September 14, 2004) and the colors represent the relative concentration pathlength of methane within the ANGEL swath. Normal background methane levels are shown in dark blue. ANGEL collector scan swath is approximately 25 meters wide and is superimposed on the base image. Elevated concentrations of methane clearly stand out in red and the highest concentrations are located north of the Gas Plant (north of location M8 on the Virtual Pipeline route). It should be noted that the imagery used as purchased was not perfectly geo-registered and is provided to give approximate context (+/- 15 meters) to the ANGEL analysis data, not absolute positioning.

If no satellite or aerial photography imagery is available for a survey, the ANGEL aircraft has been fitted with a monochrome video camera that is used for flight path verification. This camera collects looking forward at 15 degrees from nadir and provides MPEG2 motion video imagery with approximately 1.4 ft raw GSD resolution. A sample frame is shown below. The video camera currently in use was designed only to provide engineering flight test information and will soon be replaced with a much higher resolution color and false color IR digital camera designed to collect a continuous strip of geo-referenced imagery as the sensor is flown along the pipeline right-of-way.

The ANGEL aircraft image below shows the RMOTC Gas Plant viewed from the North during one of the early morning passes. The yellow circle indicates the approximate location of the elevated levels of methane seen throughout the day in the Northwest corner of the Gas Plant.



Attachment 3: ITT ANGEL Customer Report – 15 Sept 2004 Collection

ANGEL Service Customer Report

Rocky Mountain Oilfield Testing Center (RMOTC) Virtual Pipeline Inspection

DATE(s) INSPECTION DATA ACQUIRED:

September 15, 2004

CONTRACT NUMBER:

DOE/National Energy Technology Laboratory Cooperative Development
Agreement # DE-FC26-03NT41877

IN RESPONSE TO RFP:

DOE Program Solicitation (PS) No. DE-PS26-02NT41613

SUBMITTED BY:

Steven Stearns
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Rochester, NY 14653-7225
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SUBMITTED TO:

Chris Buckingham
Southwest Research Labs
6220 Culebra Road (78238-5166)
P.O. Drawer 28510 (78228-0510)
San Antonio, Texas

REPORT DATE:

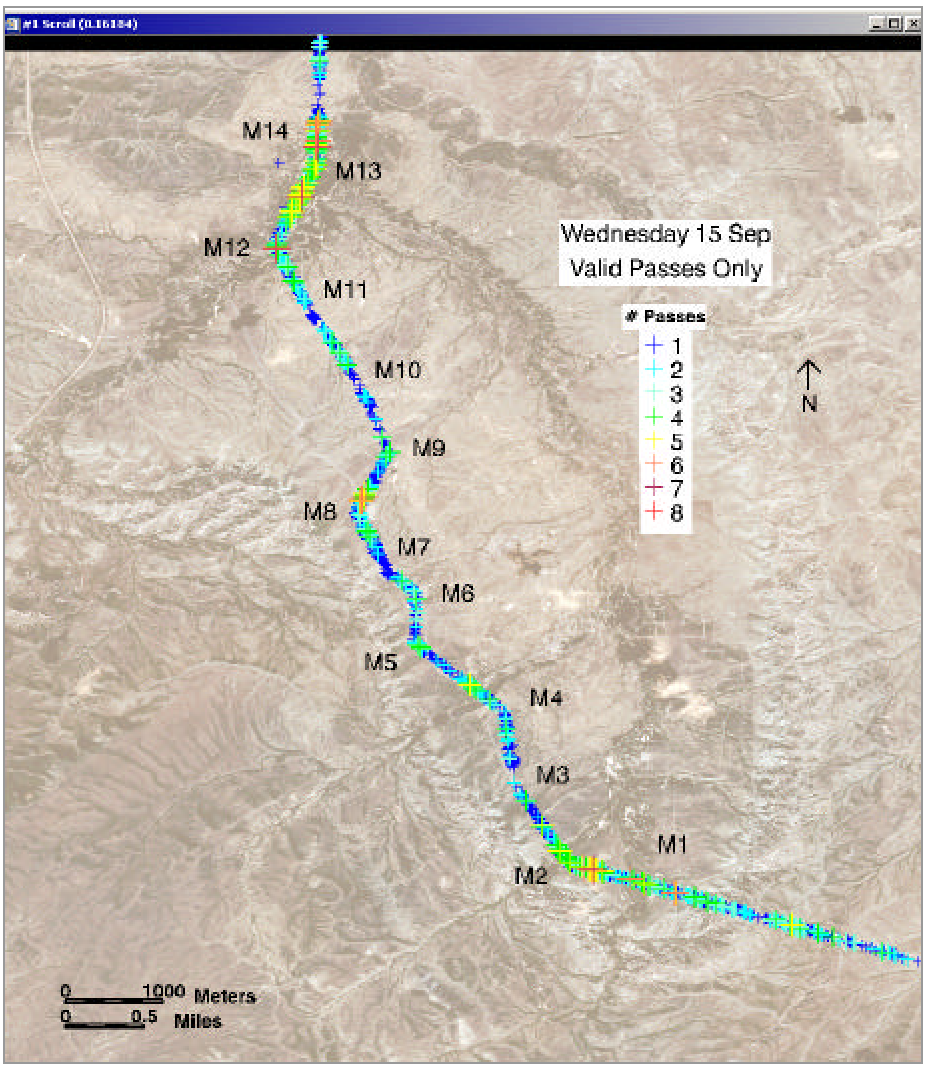
October 8, 2004

ITT Industries
Engineered for life

Executive Summary:

On September 15, 2004 the route identified as "RMOTC Virtual Pipeline" was flown with the ITT Industries ANGEL Sensor. This route was flown multiple times to ensure the complete Virtual Pipeline Route was fully covered, and to provide increased sample density to improve detection of smaller emissions. Analysis of the information collected indicates a number of areas of significant methane concentration along the pipeline right of way. The locations and relative size/concentration patterns for these are described in detail in this report.

The route flown is depicted below. All detected concentration areas are labeled with crosses. Color-coding is used to indicate detection of the methane concentration on multiple passes, with red indicating that the specific methane concentration was detected (within 30 meters) on eight separate passes. Six distinct methane concentration areas were detected with sufficient quantity and frequency (7 or 8 passes) that they are high confidence.



Methane Detections

NAD 27 Data (DMS)					
Latitude	Longitude	Date	AM Passes	PM Passes	Comments
43 15 13.374	-106 11 24.1836	15-Sep-04	1,2,3,4,5,6	1,5,6	between M1 & M2
43 15 21.69	-106 11 39.5916	15-Sep-04	4,5,6	1,2,4,5	northwest of M2
43 17 58.9236	-106 13 8.9328	15-Sep-04	1,2,4,5,6	1,3,4,5,6	north of gas plant (high confidence)
43 20 9.312	-106 13 39.972	15-Sep-04	2,3,4,6	1,4,5	area #1 between M12 & M13
43 20 15.0252	-106 13 36.498	15-Sep-04	2,3,4,5,6	1,6	area #2 between M12 & M13
43 20 38.0976	-106 13 29.28	15-Sep-04	1,4,5,6	2,3,4,5,6	area between M13 & M14

The methane emissions with the highest confidence were captured on a relatively large number of passes as indicated in the above table. The geographic coordinates provide the location of the aggregated multiple detections.

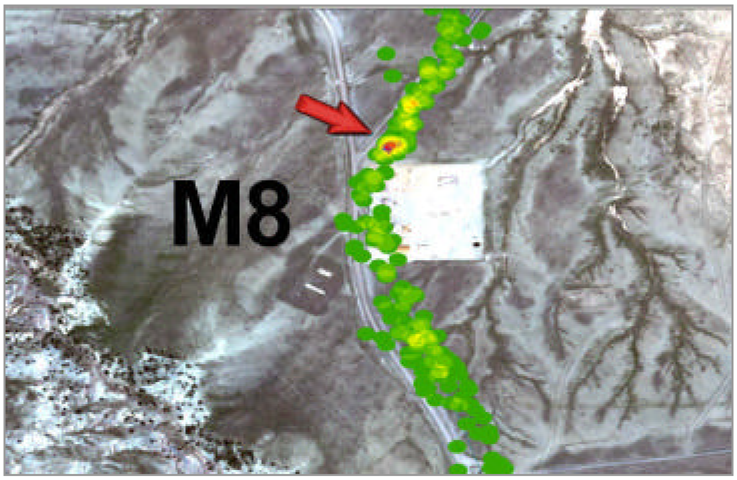
Metha ne emissions detected with lesser, but still significant confidence is listed in the table below. In all cases these were detected on multiple passes as well, but not as consistently as the detections documented above.

NAD 27 Data (DMS)			
Latitude	Longitude	Date	Comments
43 14 57.948	-106 11 27.7332	15-Sep-04	M1-M2 middle
43 19 29.9784	-106 13 50.232	15-Sep-04	M11-M12
43 19 38.6472	-106 13 54.2496	15-Sep-04	M12 corner - large area extent
43 20 4.1208	-106 13 42.4884	15-Sep-04	M12-M13
43 15 1.98	-106 11 42.324	15-Sep-04	M2
43 17 8.7396	-106 12 58.0896	15-Sep-04	M6-M7
43 17 30.8184	-106 13 14.16	15-Sep-04	M7-M8
43 15 6.786	-106 11 46.5684	15-Sep-04	
43 14 59.316	-106 11 33.0324	15-Sep-04	M1-M2 - big leak
43 20 0.9492	-106 13 43.8204	15-Sep-04	M12-M13
43 17 44.5092	-106 13 15.8808	15-Sep-04	just north of M8
43 20 23.9784	-106 13 36.3252	15-Sep-04	just south of M14
43 19 54.714	-106 13 47.1072	15-Sep-04	north of M12
43 20 17.142	-106 13 36.966	15-Sep-04	just north of M13
43 15 3.6936	-106 11 43.62	15-Sep-04	just north of M2
43 16 20.046	-106 12 24.4044	15-Sep-04	just north of M4
43 15 1.1808	-106 11 38.8716	15-Sep-04	just south of M2 - many discrete areas
43 16 59.9124	-106 12 51.7608	15-Sep-04	just south of M6
43 20 13.3116	-106 13 37.6644	15-Sep-04	just south of M13
43 19 49.0008	-106 13 49.9116	15-Sep-04	north of M12
43 15 5.1228	-106 11 44.7972	15-Sep-04	north of M2

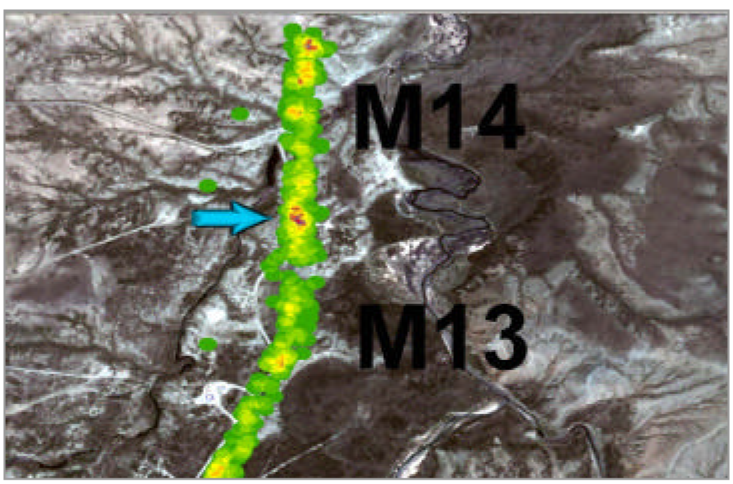
NAD 27 Data (DMS)			
Latitude	**Longitude**	**Date**	**Comments**
43 17 47.1984	-106 13 14.5956	15-Sep-04	north of M8
43 19 57.9792	-106 13 45.0264	15-Sep-04	north of M12
43 16 22.3572	-106 12 27.3528	15-Sep-04	north of M4
43 19 51.8916	-106 13 48.0252	15-Sep-04	north of M12
43 15 9.5652	-106 11 48.3612	15-Sep-04	north of M2
43 20 31.2504	-106 13 36.5376	15-Sep-04	on M14
43 15 18.63	-106 11 55.0932	15-Sep-04	single M2-M3
43 18 45.8568	-106 13 22.3068	15-Sep-04	single north of M10
43 15 29.7684	-106 12 1.8612	15-Sep-04	single south of M3
43 16 38.9388	-106 12 49.554	15-Sep-04	small areas just south of M5
43 16 7.2192	-106 12 11.3256	15-Sep-04	small area just south of M4
43 20 28.6656	-106 13 36.2064	15-Sep-04	small areas just south of M14
43 16 5.502	-106 12 11.2752	15-Sep-04	south of M4
43 20 8.9772	-106 13 40.2024	15-Sep-04	tiny area south of M13
43 16 41.1564	-106 12 51.678	15-Sep-04	tiny area at M5
43 17 38.5584	-106 13 17.076	15-Sep-04	tiny area just south of M8
43 18 5.2884	-106 13 4.278	15-Sep-04	tiny areas just south of M9
43 19 22.0044	-106 13 45.6276	15-Sep-04	tiny area north of M11
43 14 54.7188	-106 11 15.9504	15-Sep-04	vicinity of calibration leak

Significant Emissions

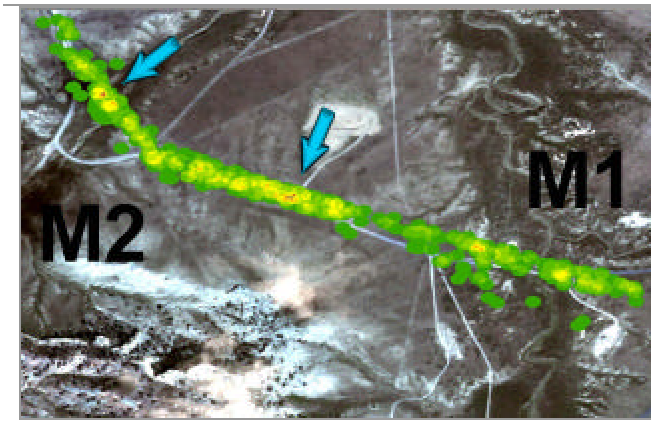
In this survey there are six areas that stand out due to the size and concentration-pathlength values of methane plume and frequency of detection. These are identified in the images provided below with red and orange plume markers. The green markers are areas where there were potential indicators for methane but these were only detected on single passes. These do not represent highly significant indicators.



- N 43 17 58.9236
- W -106 13 8.9328
- Detected on 10 passes
- North of Gas Plant

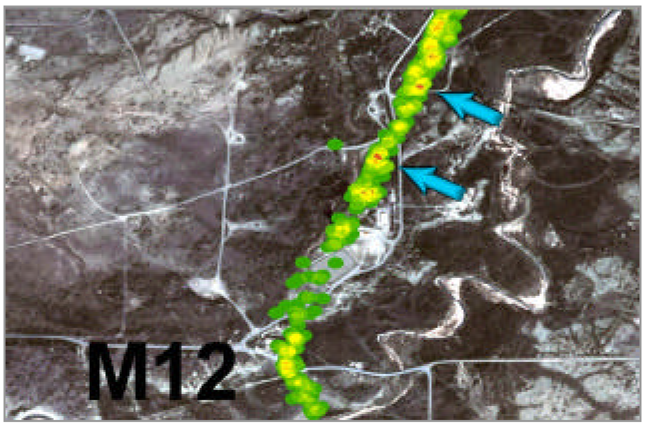


- N 43 20 23.68
- W -106 13 36.43
- Detected on 9 passes



- N 43 15 7.23
- W -106 11 46.72
- Detected on 7 passes

- N 43 14 58.91
- W -106 11 31.31
- Detected on 9 passes



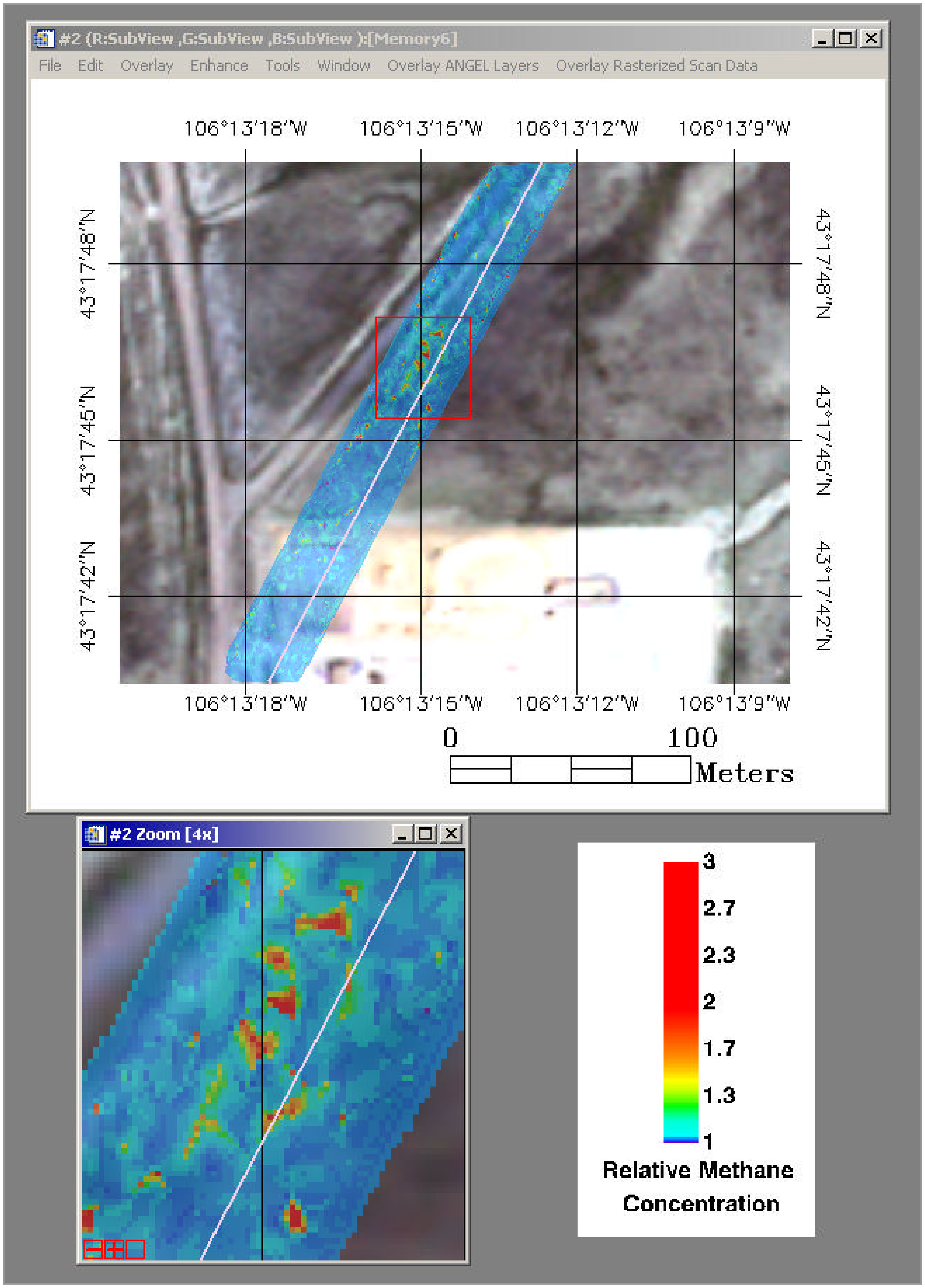
- N 43 20 9.312
- W -106 13 39.972
- Detected on 7 passes

- N 43 20 15.0252
- W -106 13 36.498
- Detected on 7 passes

Special Case Analysis

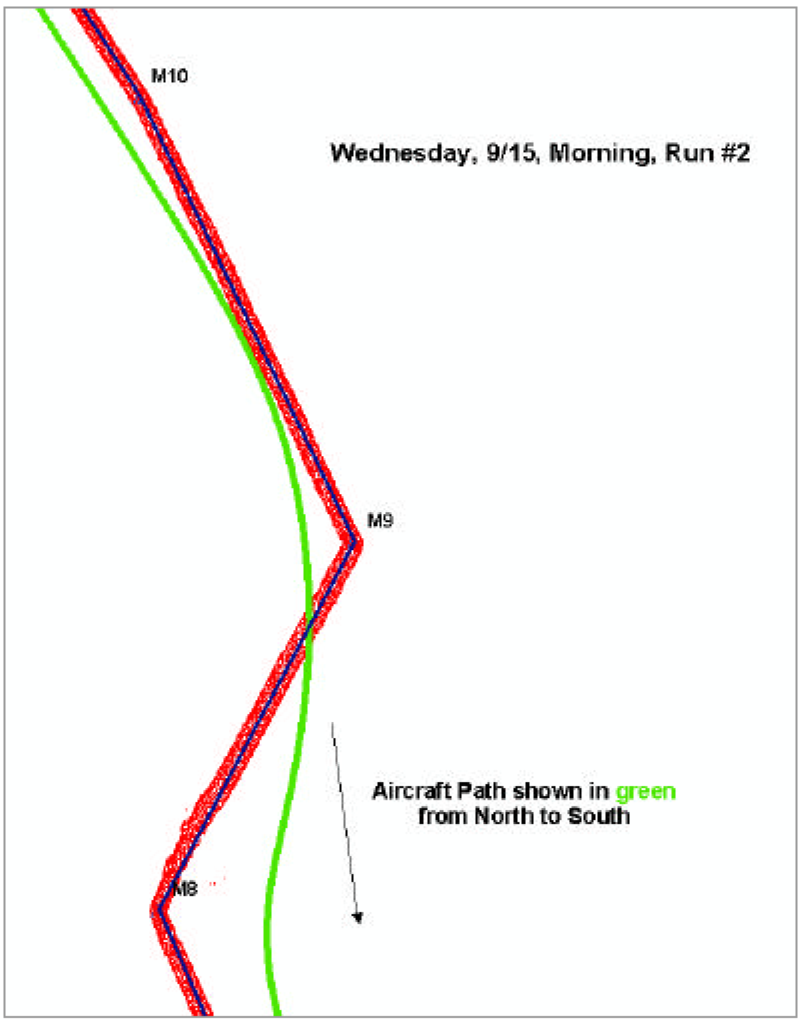
From the collection on Wednesday, September 15, 2004, a location North of the Gas Plant stood out above all the others and warranted additional analysis. A raster-based analysis and methane images of the RMOTC Gas Plant area are shown below. The methane concentration pathlengths were measured from a single pass (2nd pass on the morning of September 15, 2004) and the colors represent the relative concentration pathlength of methane within the ANGEL swath. Normal background methane levels are shown in dark blue. ANGEL collector scan swath is approximately 25 meters wide and is superimposed on the base image. Elevated concentrations of methane clearly stand out in red. Over the course of the day, elevated level of methane were seen in a zone stretching from the NW corner of the Gas Plant to a point roughly 30-40 meters to the northeast. The image shown below is the result of analysis of thousands of individual methane measurements. The patchy nature of the highlighted plume is at least partially due to the algorithms used to analyze the ANGEL data stream. In reality the plume is likely to be somewhat more homogenous in nature.

The base imagery for this analysis is from a Quickbird multispectral collection provided by DOE/NETL. It should be noted that the imagery used as purchased was not perfectly geo-registered and is provided to give approximate context (+/- 15 meters) to the ANGEL analysis data, not absolute positioning.


#2 (R:SubView ,G:SubView ,B:SubView):[Memory6]
File Edit Overlay Enhance Tools Window Overlay ANGEL Layers Overlay Rasterized Scan Data
106°13'18"W
106°13'15"W
106°13'12"W
106°13'9"W
43°17'48"N
43°17'45"N
43°17'42"N
0
100
Meters
#2 Zoom [4x]
3
2.7
2.3
2
1.7
1.3
1
Relative Methane Concentration

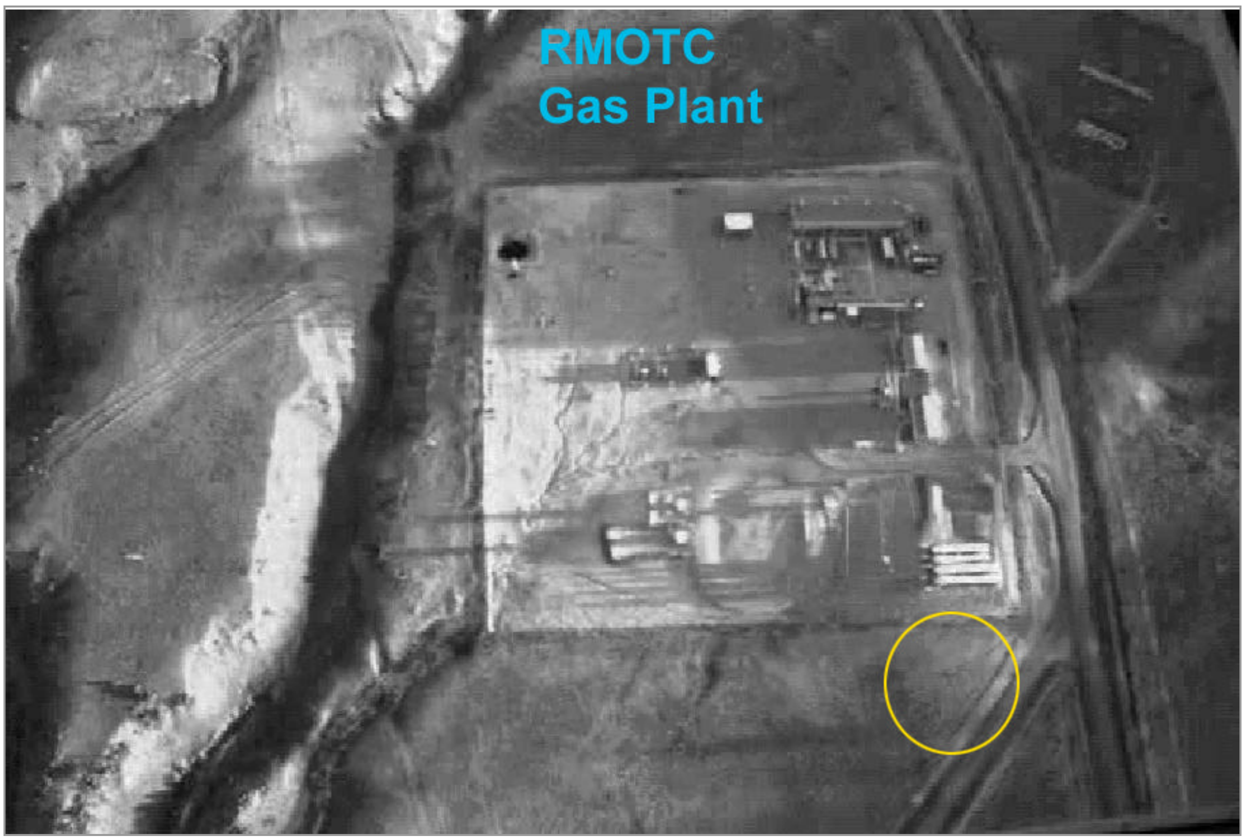
Right of Way Coverage

ANGEL collection planning starts with developing a flight plan that will place the aircraft over the pipeline route. In most cases the aircraft flight path cannot perfectly match the pipeline route but the ANGEL sensor can still track the full right of way. This is important to ensure that we provide adequate collection coverage of the full right of way for the entire length of the pipeline segment being surveyed. As the aircraft flies the designated route, the sensor tracks and images the actual right of way, even when not directly under the aircraft and regardless of minor flight variations. The information collected from each flight is analyzed to determine that the right of way was fully covered as planned. The graphic below shows the actual results from a small segment of one such flight path over the designated pipeline route. The green line is the path of the aircraft and the red band is made up of all the individual sensor collects throughout the flight. In this case the sensor accurately tracked the pipeline and provided full coverage of the right of way. This post flight analysis provides confidence that we have adequately covered the pipeline path and right-of-way for the full 7.5-mile length of the survey.



Flight Path Verification

The ANGEL aircraft has been fitted with a monochrome video camera that is used for flight path verification. This camera collects looking forward at 15 degrees from nadir and provides MPEG2 motion video imagery with approximately 1.4 ft raw GSD resolution. A sample frame is shown below from one of the PM passes. The video camera currently in use was designed only to provide engineering flight test information. It will soon be replaced with a much higher resolution color and false color IR digital camera designed to collect a continuous strip of geo-referenced imagery as the sensor is flown along the pipeline right-of-way. The image below was acquired during a PM run as the ANGEL aircraft was inspecting the pipe from North to South. The yellow circle indicates the approximate area North of the RMOTC Gas Plant in which elevated levels of methane were detected.



Attachment 4: ITT ANGEL Customer Report – 16 Sept 2004 Collection

ANGEL Service Customer Report

Rocky Mountain Oilfield Testing Center (RMOTC) Virtual Pipeline Inspection

DATE(s) INSPECTION DATA ACQUIRED:

September 16, 2004

CONTRACT NUMBER:

DOE/National Energy Technology Laboratory Cooperative Development Agreement # DE-FC26-03NT41877

IN RESPONSE TO RFP:

DOE Program Solicitation (PS) No. DE-PS26-02NT41613

SUBMITTED BY:

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SUBMITTED TO:

Chris Buckingham
Southwest Research Labs
6220 Culebra Road (78238-5166)
P.O. Drawer 28510 (78228-0510)
San Antonio, Texas

REPORT DATE:

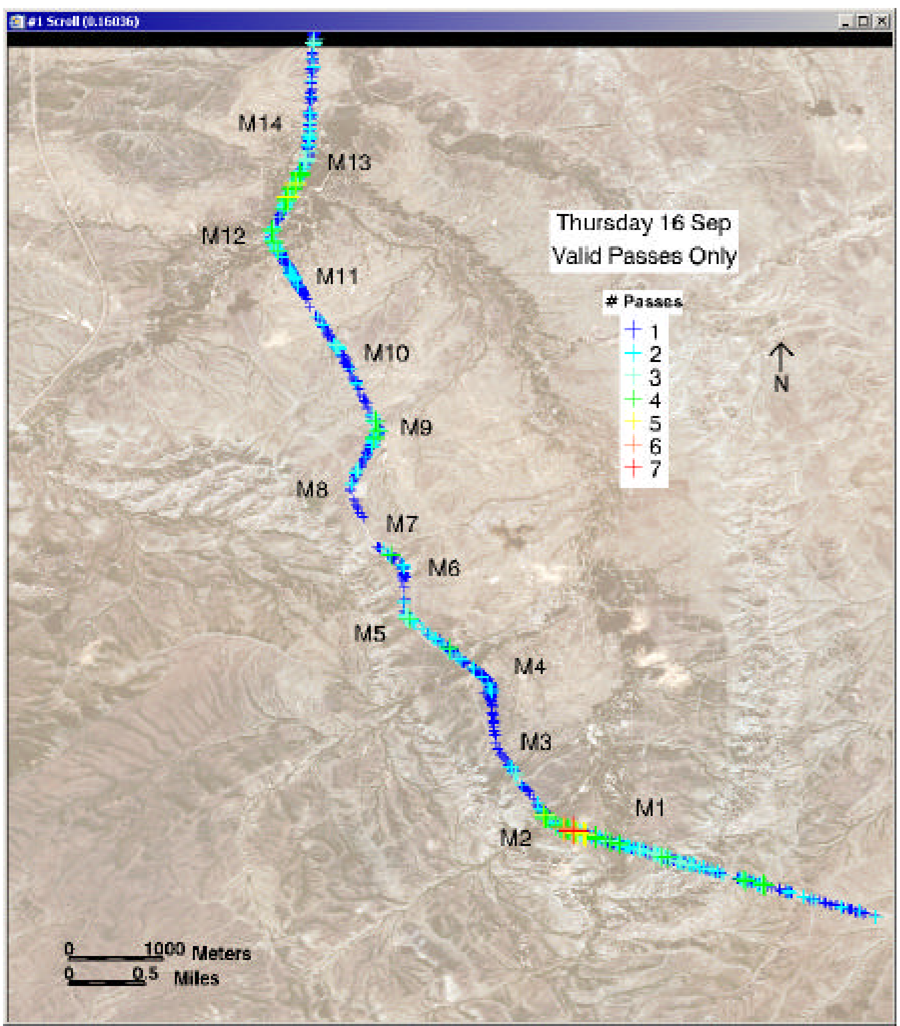
October 8, 2004

ITT Industries
Engineered for life

Executive Summary:

On September 16, 2004 we flew the route identified as "RMOTC Virtual Pipeline" with the ITT Industries ANGEL Sensor. This route was flown multiple times to ensure we had fully covered the complete Virtual Pipeline Route and to provide increased sample density to improve detection of smaller emissions. Analysis of the information collected indicates a number of areas of significant methane concentration along the pipeline right of way. The locations and relative size/concentration patterns for these are described in detail in this report.

The route flown is depicted below. All detected concentration areas are labeled with crosses. Color-coding is used to indicate detection of the methane concentration on multiple passes, with red indicating that the specific methane concentration was detected (within 30 meters) on seven separate passes. A number of distinct methane concentration "hot spots" were detected with sufficient quantity and frequency that they are very high confidence. Note that there are multiple "hot spots" in the vicinity of M2, which could indicate several smaller or a single large methane emission (see the Special Case Analysis later in this report).



Methane Detections

The methane emissions with the highest confidence were captured on a relatively large number of passes as indicated in this table. The geographic coordinates provide the location of the aggregated multiple detections.

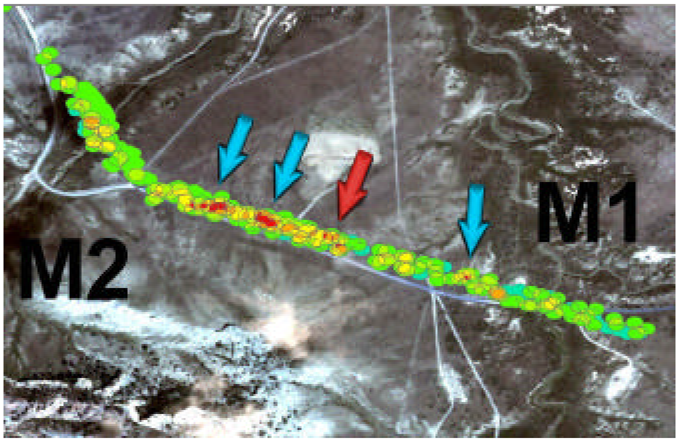
NAD 27 Data (DMS)					
Latitude	Longitude	Date	AM Passes	PM Passes	Comments
43 14 55.2408	-106 11 17.322	16-Sep-04	1,2,3,4,6	5,6	area #1 between M1 & M2
43 14 58.1352	-106 11 27.726	16-Sep-04	1,2,3,4,5,6,7	5,6	area #2 between M1 & M2
43 14 59.6544	-106 11 32.8236	16-Sep-04	1,2,3,4,6,7	5,6	area #3 between M1 & M2
43 15 0.7272	-106 11 36.8484	16-Sep-04	1,2,3,4,6,7	5,6	area #4 between M1 & M2
43 16 39.0504	-106 12 50.0508	16-Sep-04	2,3,4,5,7	5,6	area southeast of M5
43 18 11.2464	-106 13 5.2284	16-Sep-04	1,2,3,4,7	5,6	area northwest of M9
43 19 40.9188	-106 13 53.9472	16-Sep-04	1,2,3,4,6,7	5,6	area #1 between M12 & M13
43 20 0.24	-106 13 44.04	16-Sep-04	1,2,5,6,7	6	area #2 between M12 & M13
43 20 3.2892	-106 13 42.6108	16-Sep-04	1,2,3,6,7	5,6	area #3 between M12 & M13

Methane emissions detected with lesser, but still significant confidence are listed in the table below. In all cases these were detected on multiple passes as well, but not as consistently as the detections documented above.

NAD 27 Data (DMS)			
Latitude	Longitude	Date	Comments
43 14 59.4276	-106 11 32.4816	16-Sep-04	M1-M2
43 14 53.2212	-106 11 10.8924	16-Sep-04	M1
43 20 14.5392	-106 13 37.6788	16-Sep-04	M13
43 16 24.8268	-106 12 30.69	16-Sep-04	M4-M5
43 16 39.6264	-106 12 50.6016	16-Sep-04	M5
43 17 8.6028	-106 12 58.428	16-Sep-04	M6-M7
43 18 7.4916	-106 13 4.2852	16-Sep-04	M9
43 19 40.8972	-106 13 53.9652	16-Sep-04	just north of M12
43 16 15.8808	-106 12 19.728	16-Sep-04	just north of M4
43 16 19.1316	-106 12 24.8364	16-Sep-04	just north of M4
43 19 35.76	-106 13 52.8996	16-Sep-04	just south of M12
43 19 54.8292	-106 13 47.0424	16-Sep-04	large area M12-M13
43 20 0.4416	-106 13 44.4	16-Sep-04	medium area M12-M13
43 14 54.3012	-106 11 15.4608	16-Sep-04	north of M1
43 18 46.7712	-106 13 23.0952	16-Sep-04	north of M10
43 20 23.7336	-106 13 36.2496	16-Sep-04	north of M13
43 15 6.3324	-106 11 45.6072	16-Sep-04	north of M2
43 17 48.5916	-106 13 13.7388	16-Sep-04	north of M8
43 18 11.1312	-106 13 5.0448	16-Sep-04	north of M9
43 14 56.3856	-106 11 22.1028	16-Sep-04	north of north of M1
43 18 13.1616	-106 13 6.24	16-Sep-04	north of north of M9
43 20 6.8676	-106 13 40.8	16-Sep-04	northern M12-M13
43 20 3.1704	-106 13 42.5928	16-Sep-04	northern area M12-M13
43 15 27.7668	-106 12 0.3528	16-Sep-04	single poly
43 19 31.2276	-106 13 50.862	16-Sep-04	south of M12
43 18 3.4668	-106 13 5.9772	16-Sep-04	south of M9

Significant Emissions

In this survey there are a number of areas that stand out due to the size and concentration-pathlength values of methane plume and frequency of detection. These are identified in the images provided below with red and orange plume markers. The green markers are areas where there were potential indicators for methane but these were only detected on single passes. These do not represent highly significant indicators. Arrows indicate the positions of each significant emission detected.

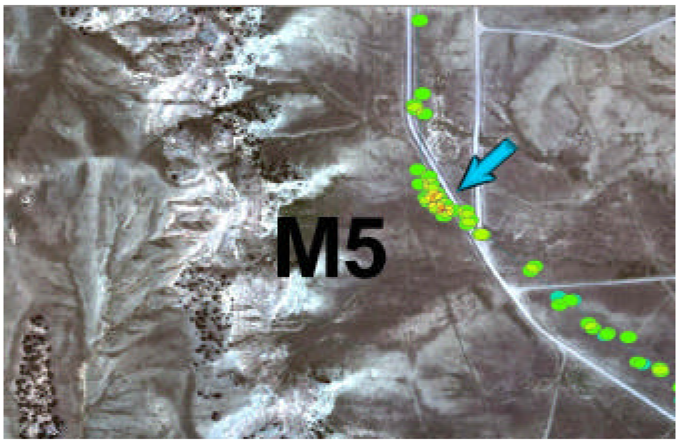


- N 43 15 0.7272
- W -106 11 36.8484
- Detected on 8 passes

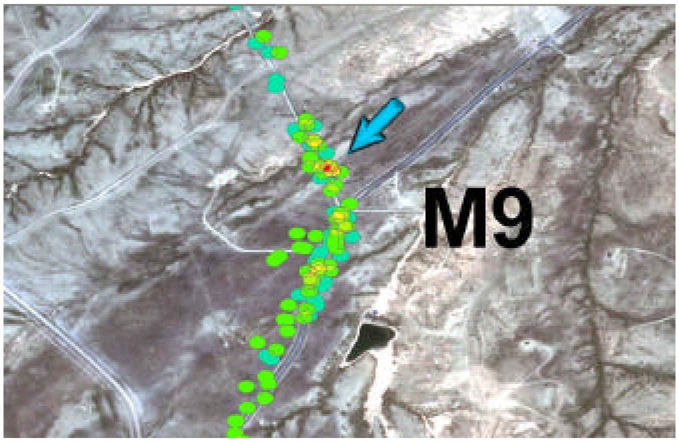
- N 43 14 59.6544
- W -106 11 32.8236
- Detected on 8 passes

- N 43 14 58.1352
- W -106 11 27.726
- Detected on 9 passes
- High confidence

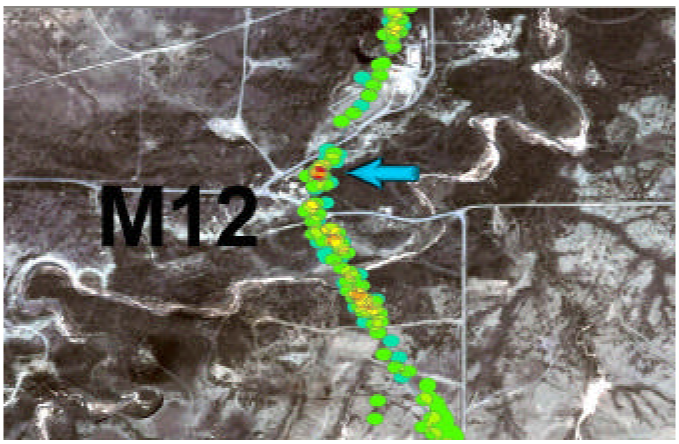
- N 43 14 55.2408
- W -106 11 17.322
- Detected on 7 passes



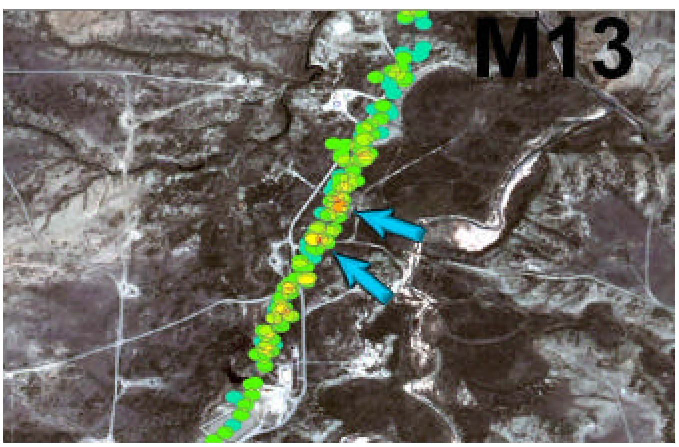
- N 43 16 39.0504
- W -106 12 50.0508
- Detected on 7 passes



- N 43 18 11.2464
- W -106 13 5.2284
- Detected on 7 passes



- N 43 19 40.9188
- W -106 13 53.9472
- Detected on 8 passes



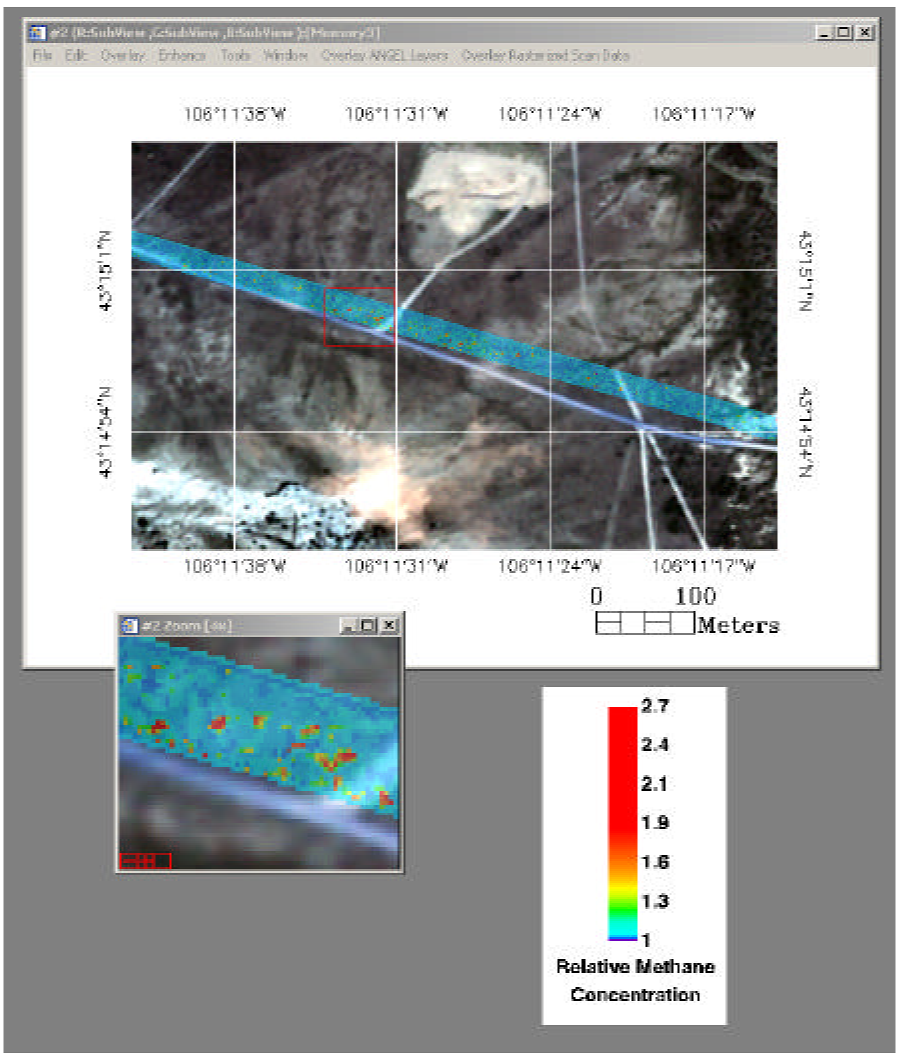
- N 43 20 3.2892
- W -106 13 42.6108
- Detected on 7 passes

- N 43 20 0.24
- W -106 13 44.04
- Detected on 6 passes

Special Case Analysis

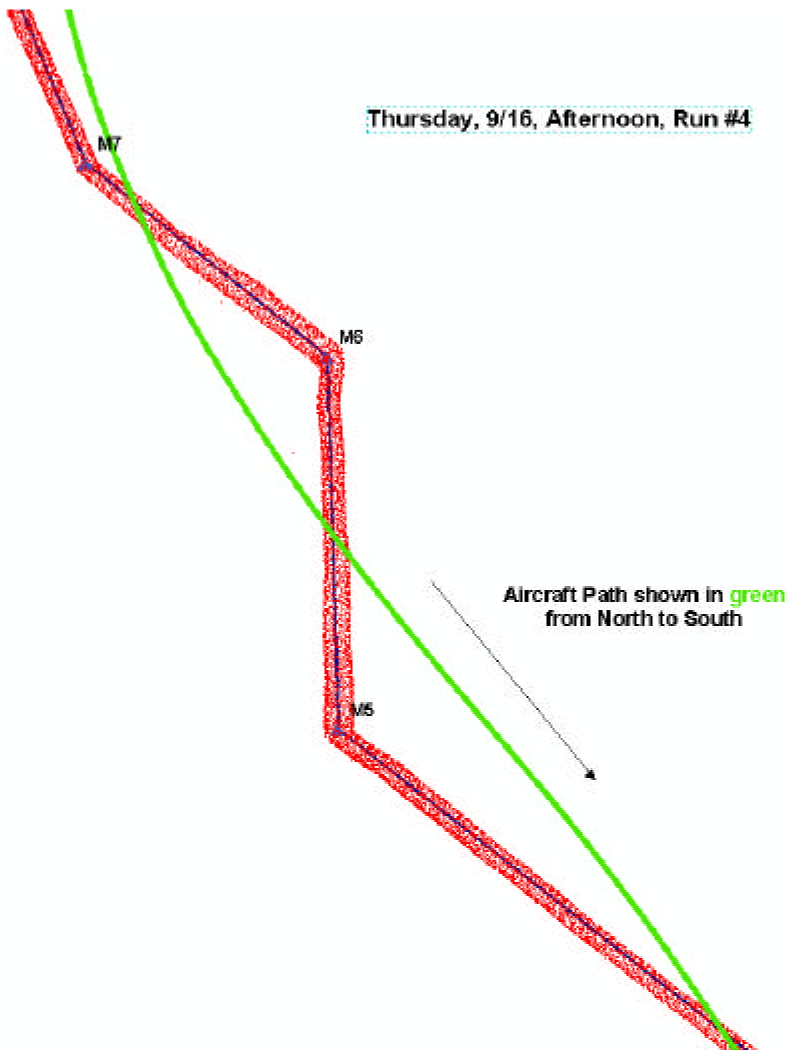
From the collection on Thursday, September 16, 2004, one location stood out and warranted additional analysis. This was the area of multiple methane "hot spots" east of Virtual Pipeline Marker 2 (M2). Multiple high methane areas were seen on multiple passes throughout the day. Raster-based analysis and methane images of the significant emissions are shown below. ANGEL data analysis suggests the possibility of leaks in the area between M1 and M2.

The base imagery for this analysis is from a Quickbird multispectral collection provided by DOE/NETL. The methane concentration pathlengths were measured from a single pass (4th pass on the afternoon of September 16, 2004) and the colors represent the relative concentration pathlength of methane within the ANGEL swath. Normal background methane levels are shown in dark blue. ANGEL collector scan swath is approximately 25 meters wide and is superimposed on the base image. It should be noted that the imagery used as purchased was not perfectly geo-registered and is provided to give approximate context (+/- 15 meters) to the ANGEL analysis data, not absolute positioning.



Right of Way Coverage

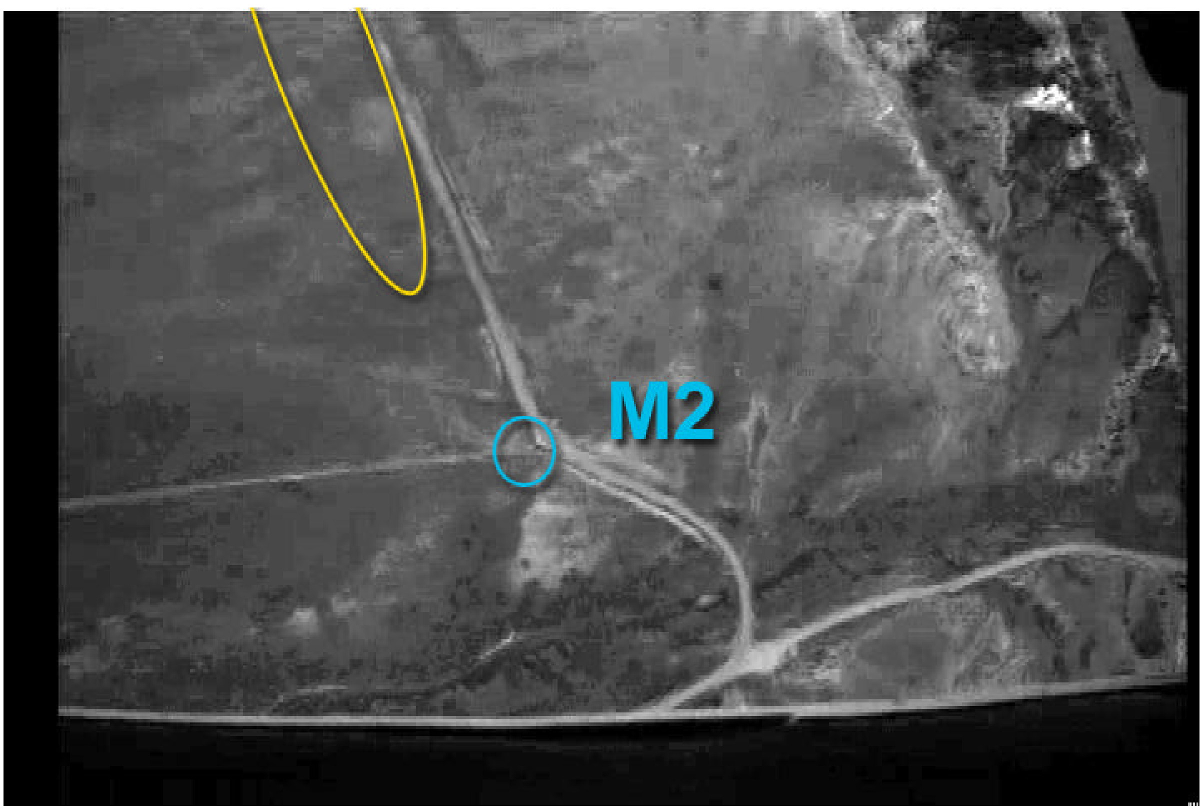
ANGEL collection planning starts with developing a flight plan that will place the aircraft over the pipeline route. In most cases the aircraft flight path cannot perfectly match the pipeline route but the ANGEL sensor can still track the full right of way. This is important to ensure that we provide adequate collection coverage of the full right of way for the entire length of the pipeline segment being surveyed. As the aircraft then flies the designated route, the sensor tracks and images the actual right of way, even when not directly under the aircraft and regardless of minor flight variations. The information collected from each flight is analyzed to determine that the right of way was fully covered as planned. The graphic below shows the actual results from a small segment of one such flight path over the designated pipeline route. The green line is the path of the aircraft and the red band is made up of all the individual sensor collects throughout the flight. In this case the sensor accurately tracked the pipeline and provided full coverage of the right of way. This post flight analysis provides confidence that we have adequately covered the pipeline path and right-of-way for the full 7.5-mile length of the survey.



Flight Path Verification

The ANGEL aircraft has been fitted with a monochrome video camera that is used for flight path verification. This camera collects looking forward at 15 degrees from nadir and provides MPEG2 motion video imagery with approximately 1.4 ft raw GSD resolution. A sample frame is shown below. The video camera currently in use was designed only to provide engineering flight test information and will soon be replaced with a much higher resolution color and false color IR digital camera designed to collect a continuous strip of geo-referenced imagery as the sensor is flown along the pipeline right-of-way.

The image below was taken from the East as the ANGEL aircraft was finishing up a North to South inspection pass. The approximate location of Marker 2 is noted. The location of the western edge of the M1-M2 zone of elevated methane detections is highlighted with a yellow ellipse.



Attachment 5: ITT ANGEL Customer Report – 17 Sept 2004 Collection

ANGEL Service Customer Report

Rocky Mountain Oilfield Testing Center (RMOTC) Virtual Pipeline Inspection

DATE(s) INSPECTION DATA ACQUIRED:

September 17,2004

CONTRACT NUMBER:

DOE/National Energy Technology Laboratory Cooperative Development Agreement # DE-FC26-03NT41877

IN RESPONSE TO RFP:

DOE Program Solicitation (PS) No. DE-PS26-02NT41613

SUBMITTED BY:

STEVEN STEARNS

ITT Industries Space Systems Division
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SUBMITTED TO:

Chris Buckingham
Southwest Research Labs
6220 Culebra Road (78238-5166)
P.O. Drawer 28510 (78228-0510)
San Antonio, Texas

ITT Industries
Engineered for life

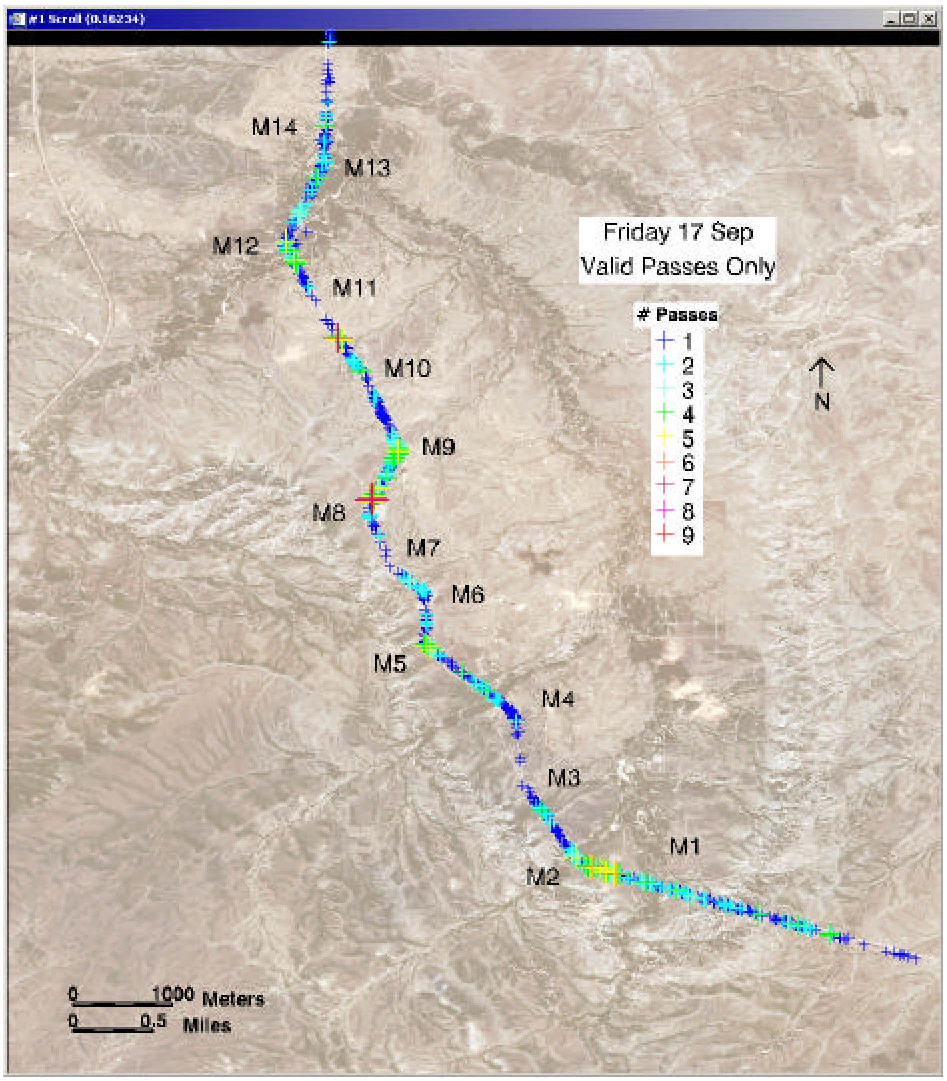
REPORT DATE:

October 8, 2004

Executive Summary:

On September 17, 2004 we flew the route identified as "RMOTC Virtual Pipeline" with the ITT Industries ANGEL Sensor. This route was flown multiple times to ensure we had fully covered the complete Virtual Pipeline Route and to provide increased sample density to improve detection of smaller emissions. Analysis of the information collected indicates a number of areas of significant methane concentration along the pipeline right of way. The locations and relative size/concentration patterns for these are described in detail in this report.

The route flown is depicted below. All detected concentration areas are labeled with crosses. Color-coding is used to indicate detection of the methane concentration on multiple passes, with red indicating that the specific methane concentration was detected (within 30 meters) on nine separate passes. Six distinct methane concentration areas were detected with sufficient quantity and frequency (7, 8 or 9 passes) that they are very high confidence.



Methane Detections

The methane emissions with the highest confidence were captured on a relatively large number of passes as indicated in this table. The geographic coordinates provide the location of the aggregated multiple detections.

NAD 27 Data (DMS)					
Latitude	**Longitude**	**Date**	**AM Passes**	**PM Passes**	**Comments**
43 14 57.8148	-106 11 27.4776	17-Sep-04	2,3,4,5,6	2,3	area #1 between M1 & M2
43 14 58.7472	-106 11 31.8408	17-Sep-04	1,2,3,4,6	2,3	area #2 between M1 & M2
43 15 1.1592	-106 11 37.8132	17-Sep-04	1,2,3,6,7	1,3	area #3 between M1 & M2
43 17 44.8908	-106 13 15.8556	17-Sep-04	1,2,4,5,6,7	1,2,3	north of gas plant (high confidence)
43 18 56.9124	-106 13 31.0548	17-Sep-04	2,3,4,5,6,7	2	area between M10 & M11
43 19 40.0116	-106 13 53.8824	17-Sep-04	1,2,3,4,5	3,4	area northeast of M12

Methane emissions detected with lesser, but still significant confidence are listed in the table below. In all cases these were detected on multiple passes as well, but not as consistently as the detections documented above.

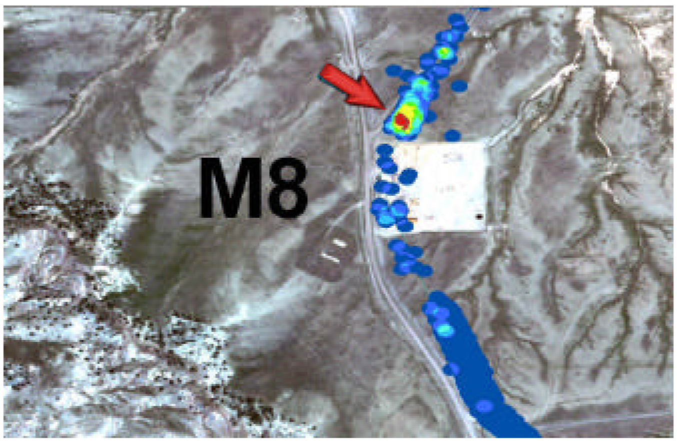
NAD 27 Data (DMS)			
Latitude	**Longitude**	**Date**	**Comments**
43 16 14.322	-106 12 17.3376	17-Sep-04	
43 15 27.0432	-106 12 0.3456	17-Sep-04	M2-M3
43 17 45.726	-106 13 15.2076	17-Sep-04	already have M8 (gas plant)
43 19 40.08	-106 13 53.8104	17-Sep-04	already have just north of M12
43 14 57.912	-106 11 27.348	17-Sep-04	already have north of M1
43 18 56.6784	-106 13 30.3636	17-Sep-04	already have south of M11
43 15 0.1368	-106 11 34.7856	17-Sep-04	already have south of M2
43 15 1.0908	-106 11 38.4576	17-Sep-04	already have vic M2
43 15 5.5692	-106 11 45.0132	17-Sep-04	just north of M2
43 14 59.0244	-106 11 31.7436	17-Sep-04	north of already have north of M1
43 19 51.2508	-106 13 48.5724	17-Sep-04	single sliver M12-M13
43 19 36.1452	-106 13 52.554	17-Sep-04	sliverama just south of M12
43 19 30.7308	-106 13 50.07	17-Sep-04	sliverama south of M12
43 14 53.7108	-106 11 13.5456	17-Sep-04	vic M1
43 16 40.3032	-106 12 51.1956	17-Sep-04	vic M5
43 18 6.246	-106 13 4.044	17-Sep-04	vic M9

Methane emissions detected at the location of the 5,000 scfh "calibration leak" were analyzed separately. A GIS analysis of just the Friday PM passes indicate that the leak was detected on three passes. The position of that leak is shown in the following table.

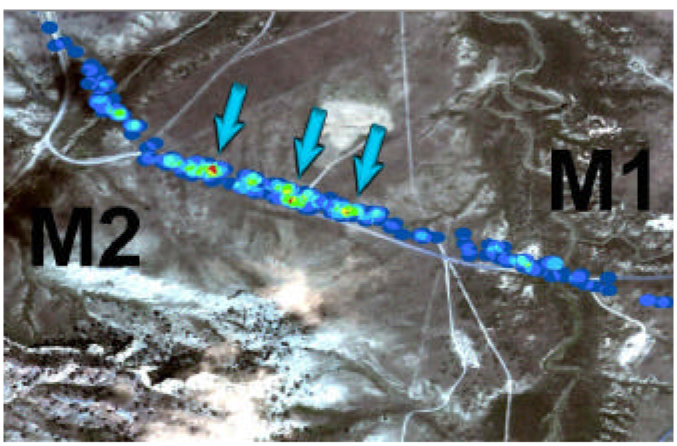
NAD 27 Data (DMS)					
Latitude	**Longitude**	**Date**	**AM Passes**	**PM Passes**	**Comments**
43 14 53.7036	-106 11 13.434	17-Sep-04	N/A	1,2,3	Calibration leak

Significant Emissions

In this survey there are six areas that stand out due to the size and concentration-pathlength values of methane plume and frequency of detection. These are identified in the images provided below with red and orange plume markers. The green markers are areas where there were potential indicators for methane but these were only detected on single passes and at low concentration pathlengths. These do not represent highly significant indicators. In addition, the 5,000 scfh calibration leak near M1was overflown and detected three times on Friday PM and is illustrated below.



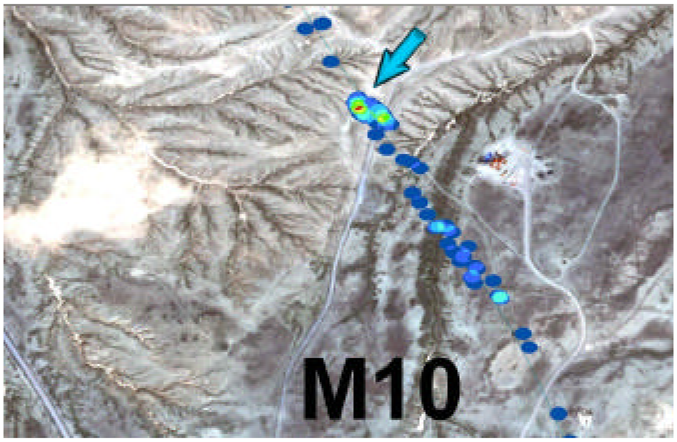
- N 43 17 44.8908
- W -106 13 15.8556
- Detected on 9 passes
- N of Gas Plant (High Confidence)



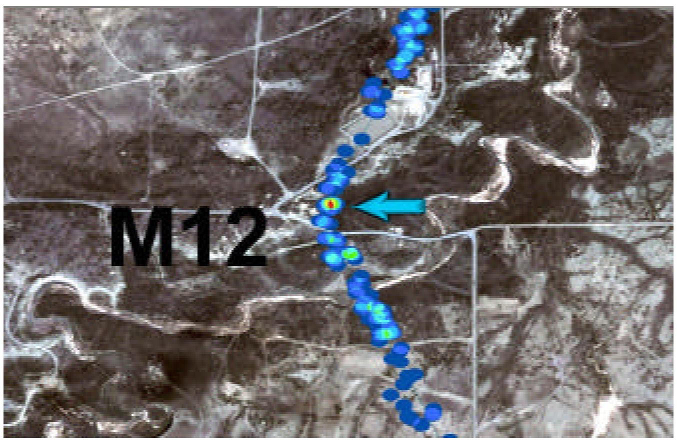
- N 43 15 1.1592
- W -106 11 37.8132
- Detected on 7 passes

- N 43 14 58.7472
- W -106 11 31.8408
- Detected on 7 passes

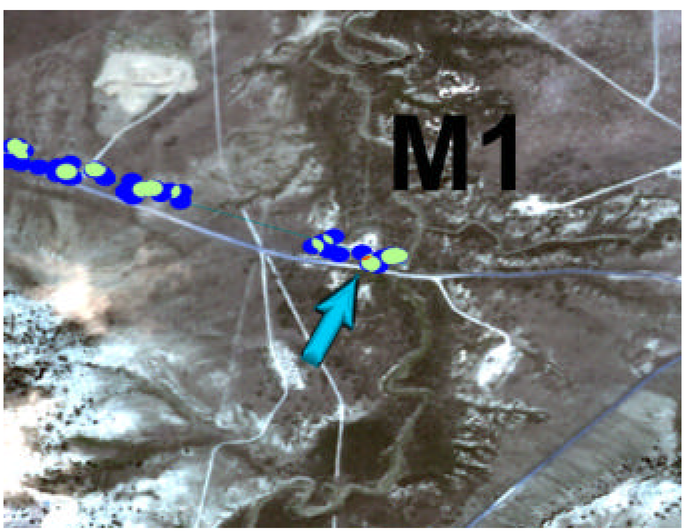
- N 43 14 57.8148
- W -106 11 27.4776
- Detected on 7 passes



- N 43 18 56.9124
- W -106 13 31.0548
- Detected on 7 passes



- N 43 19 40.0116
- W -106 13 53.8824
- Detected on 7 passes

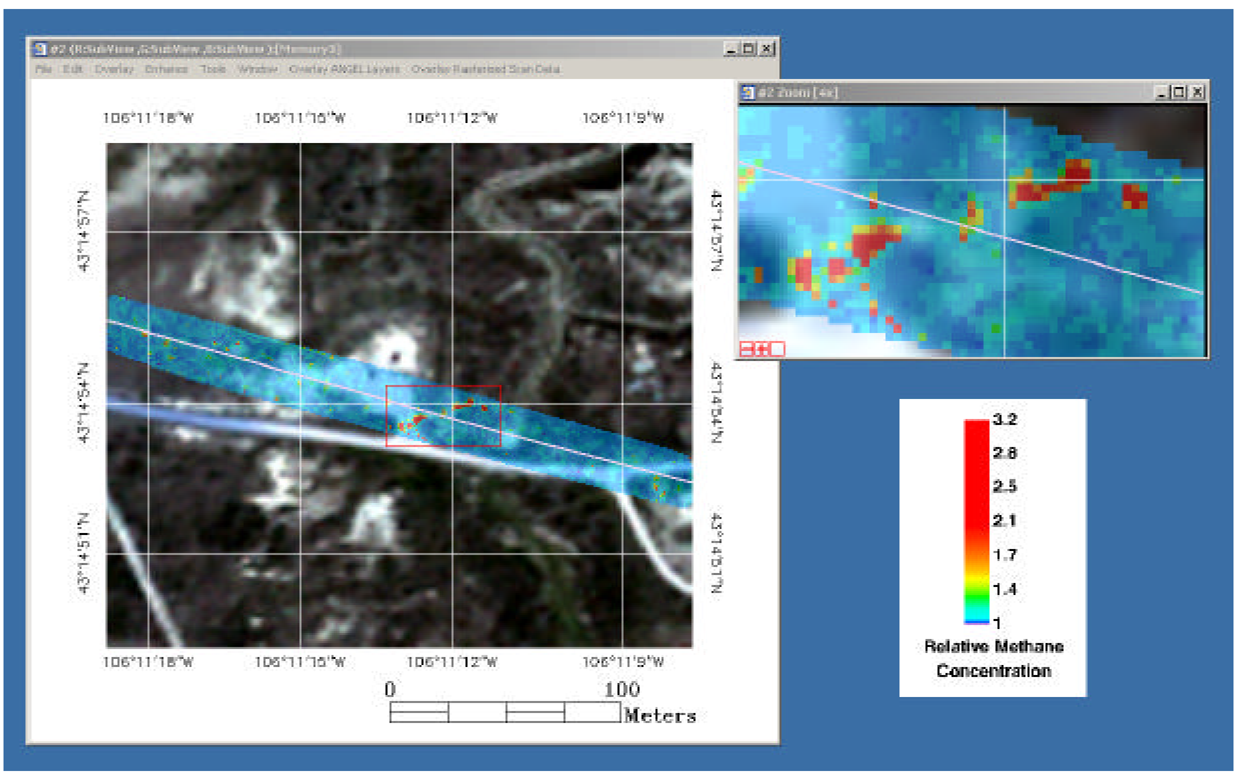


- N 43 14 53.7036
- W -106 11 13.434
- 5,000 scfh Calibration Leak detected on all three of PM passes

Special Case Analysis

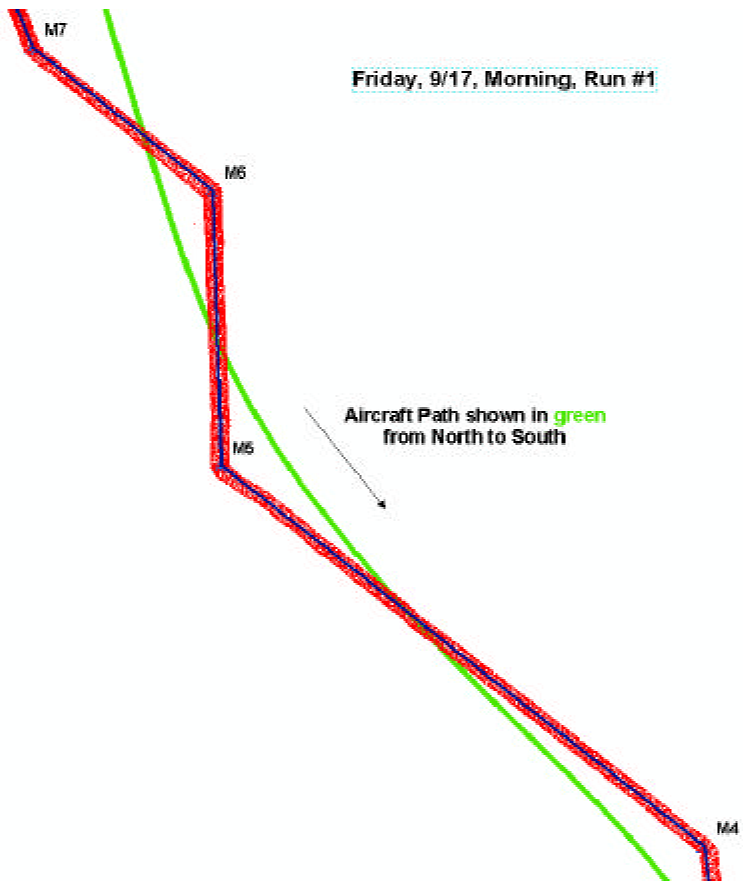
From the collection on Friday, September 17, 2004 one location stood out above all the others and warranted additional analysis. This was the 5,000 scfh "calibration leak"near M1 observed on the 3rd flight that afternoon. A raster-based analysis and methane images of the significant emissions are shown below. In this case the methane detected from the calibrated leak appears as an elongate plume.

The base imagery for this analysis is from Quickbird multispectral collection provided by DOE/NETL. The methane concentration pathlengths were measured from a single pass and the colors represent the relative concentration pathlength of methane within the ANGEL swath. Normal background methane levels are shown in dark blue. The ANGEL collection scan swath is approximately 25 meters wide and is superimposed on the base image. It should be noted that the imagery used as purchased was not perfectly geo-registered and is provided to give approximate context (+/- 15 meters) to the ANGEL analysis data, not absolute positioning.



Right of Way Coverage

ANGEL collection planning starts with developing a flight plan that will place the aircraft over the pipeline route. In most cases the aircraft flight path cannot perfectly match the pipeline route but the ANGEL sensor can still track the full right of way. This is important to ensure that we provide adequate collection coverage of the full right of way for the entire length of the pipeline segment being surveyed. As the aircraft then flies the designated route, the sensor tracks and images the actual right of way, even when not directly under the aircraft and regardless of minor flight variations. The information collected from each flight is analyzed to determine that the right of way was fully covered as planned. The graphic below shows the actual results from a small segment of one such flight path over the designated pipeline route. The green line is the path of the aircraft and the red band is made up of all the individual sensor collects throughout the flight. In this case the sensor accurately tracked the pipeline and provided full coverage of the right of way. This post flight analysis provides confidence that we have adequately covered the pipeline path and right-of-way for the full 7.5-mile length of the survey.



Flight Path Verification

The ANGEL aircraft has been fitted with a monochrome video camera that is used for flight path verification. This camera collects looking forward at 15 degrees from nadir and provides MPEG2 motion video imagery with approximately 1.4 ft raw GSD resolution. The video camera currently in use was designed only to provide engineering flight test information and will soon be replaced with a much higher resolution color and false color IR digital camera designed to collect a continuous strip of geo-referenced imagery as the sensor is flown along the pipeline right-of-way.

In image of the RMOTC Gas Plant shown below was captured during an early AM S to N pass. The yellow circle North of the Gas Plant indicates the approximate position of elevated methane levels detected throughout the day on Friday 9/17/2004.